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# Undercutting and Root Wrenching of Tree Seedlings: An Annotated Bibliography

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## FOREWORD

This review is a synopsis of the readily available literature on undercutting, in-ground root pruning and root wrenching. We regret that several articles were not included if English translations were not available. Also, some titles and restricted distribution publications could not be obtained. However, we feel we have compiled a thorough and useful compendium on the topic of root pruning and wrenching which will be of use to managers and researchers alike.

## INTRODUCTION

Physical manipulation of roots while seedlings are still in the nursery beds' is practiced in many locations around the world. The purpose and procedures vary with regional problems in stock production and are therefore related to climate, species and stock production priority. While the primary objective is to produce better quality stock at the lowest cost, reported research and technical developments cover a broad spectrum.

In this report, terminology used by the authors, whose literature was cited, was incorporated into the report wherever possible. Where wording or meaning was ambiguous, or translation made direct interpretation difficult, a series of standard definitions for key terms were used (Sutton and Tinus 1983). We strongly recommend the adoption of standard terminology for the basic procedures, especially in differentiating between in-ground and out of ground root pruning. Sutton (1967) and Sutton and Tinus (1983) suggest that the term root pruning be reserved for above ground root trimming while the term undercutting is best applied to the severance of the roots of plants in situ in the nursery seedbed or transplant line. A similar appeal to this separation of definitions is made by Rook (1971). An extension to these terms would be sidecutting instead of vertical root pruning.

The topic of undercutting and root wrenching is complex and deals with many facets of plant science. This annotated bibliography is an attempt to collate and briefly summarize a large body of literature in a uniform context to increase its availability and usefulness to others.

## HISTORICAL PERSPECTIVE

Undercutting or root wrenching in some form has been used for improving bare-root seedling stock since the late nineteenth century. In the 1920's and 1930's these techniques were used by nurserymen to increase seedling production and improve bare-root stock quality. Hastings (1923) tried to lower nursery stock prices by pruning the roots of nursery seedlings in place and then culling out inferior specimens. In so doing, he produced a seedling which he considered superior to transplants, with a sturdier form and well branched root system. Root pruning depth was investigated by Wahlenberg (1925), and the best depth for yellow and white pine was reported to be 10-12 cm although pruning at greater depths (20 cm) was found to have no beneficial effect on yellow or jack pine (Janouch 1927).

By 1930, undercutting and transplanting were each identified as principal means of altering root form (Olson 1930) and halting the growth of the shoot. Foster (1932) went so far as to suggest that undercut seedlings are fundamentally better trees than transplants. In the early thirties it appeared as if general stock production practices in New Zealand were in such a state that Goudie (1935) highly recommended the operation of wrenching to "arrest the deterioration in nursery practice". Many years later Cameron and Rook (1969) suggested that wrenching was regarded as essential in New Zealand to produce a satisfactory root system and to retard shoot growth of radiata pine. Enthusiasm for these techniques also became widespread in North America around that same time. Hallman and Lott (1974) reported that 75 percent of Federal, State and private forest tree nurseries used a fixed bottom root pruner in their operations, 32 percent used a disc-type side pruner and wrenching was

practiced at 13 percent of the nurseries surveyed. However, problems arising from root pruning were ranked 12 of 26 in a list of nurserymens concerns. This put root pruning at the same level of concern in the United States as seedling storage and general cultivation practices. More recent surveys continued to show strong support and interest in operational undercutting (Abbot and Fitch 1977, Boyer and South 1984).

## EVOLUTION OF OBJECTIVES

Root pruning was first seen as a way to reduce nursery stock prices by substituting in-place pruning and culling for the more costly process of transplanting (Hastings 1923). Root pruning was later recognized as a way of modifying top-root balance (Wahlenberg 1925) and the form and function of the root system (Wahlenberg 1925, Olson 1930, Foster 1932, Goudie 1935).

With the hard economic times associated with the late 1930's and early 1940's, emphasis was again placed on the economics of stock production. Huberman (1940) saw root pruning as a means of increasing the percentage of plantable seedlings, thereby increasing nursery efficiency. Undercutting was viewed as a labour saving method which permitted the continued production of large-size planting stock (Anonymous 1942) and later as an effective means to reduce damage and labour costs during lifting (Chavasse 1978a).

Wrenching was not fully recognized as a technique separate from root pruning until the 1960's when the combination of pruning and wrenching together was seen as a complete cultural practice (Cameron and Rook 1969, Jakabffy 1969). This combined treatment was then used for conditioning stock to facilitate outplanting and improve field performance (Van Dorsser and Rook 1972).

Edgren (1975) observed that the practice of root pruning and wrenching has evolved in three ways: 1/ it has become a series of treatments rather than just one, 2/ lateral roots are cut as well as deep roots, and 3/ machinery has been developed to eliminate pruning by hand. The apparent direction for the future is to use a square spacing and precision seeding which will permit box pruning, a thorough procedure which should produce a very compact root system, eliminate root tangling (Tinus 1981a), and permit a more normal distribution of roots in the planting hole (Chavasse 1978b).

## EQUIPMENT AND OPERATIONS

Operational equipment and nursery techniques have changed with time and the introduction of new technological advances. The discussion of operational techniques and equipment is further complicated by the various functions; undercutting, sidecutting and wrenching. Specialized equipment may be used for each technique or, in some cases, modifications to the same piece of equipment may permit all or some combinations of functions to be accomplished.

A brief summary of the types of equipment and practices used for each of the major root manipulation practices has been tabulated; sidecutting is summarized in Table 1, undercutting in Table 2, root wrenching in Table 3 and various combinations of wrenching and undercutting in Table 4.

TABLE 1 Operational technique, equipment and brief results of sidecutting or lateral root pruning.

| Year | Author | Species | Equipment | Frequency | Time of year | Depth | Width from rows or plants | Comments |
|---|---|---|---|---|---|---|---|---|
| 1942 | Anonymous | ? | vertical blades | 3 | 3-0 year | ? | between rows | |
| 1957 | Stoeckeler and Jones | 1-0 red & white pine | rolling coulters | 1 | spring | ? | midpoint | |
| 1962 | Gingerich and Hertel | 2-0 Austrian pine | rolling coulters | ? | ? | ? | between rows | |
| 1965 | Burgar | 1-0 jack pine | centre mounted knife-type | once | before growth started in 2-0 year | ? | between rows | no significant effect |
| 1968 | Eis | 1-0 Douglas fir | sharp spade | ? | middle of June | 9" | between rows | |
| 1970 | Moberly | 1.5-0 Pinus radiata | ? | every 6-8 weeks | height of 10-12" | ? | -- | |
| 1972 | Eis and Long | 2-0 western hemlock and sitka spruce | sharp spade | once | hemlock in July; early in mid July for spruce | 20 cm | 5 cm | these results are applicable only to these species & nursery |
| 1972 | Van Doreser and Rook | radiata pine | rolling coulters | 4-6 week intervals | following the start of wrenching | ? | 8 cm away from trees | |
| 1974 | McKinnon and Nicholson | radiata pine | specially adapted discs | 3-4 week intervals | late Nov. for autumn sown; late Feb. for spring sown | ? | between drills | |
| 1977 | Bacon and Hawkins | Caribbean pine | vertical blades | 6 week intervals | 16 weeks prior to lifting | ? | interdrill | conditioning prescription for routine use |
| 1984 | Davey | ? | rolling coulters | ? | first one is done 10 days after first undercutting | ? | between rows | final lateral pruning is done 2-3 days before lifting |

TABLE 2 Operational technique, equipment and brief results of undercutting only.

| Year | Author | Species | Equipment | Frequency | Time of year | Depth | Comments |
|---|---|---|---|---|---|---|---|
| 1923 | Hastings | ? | draw knife | ? | fall | 5-6" | |
| 1925 | Wahlenberg | yellow and white pine | ? | ? | close of first season | 4-5" | |
| 1927 | Janouch | yellow and jack pine | sharp blade | ? | in seed bed beginning of 2nd year | 9" | |
| 1942 | Anonymous | ? | horizontal blade | ? | 3-0 year? | 4-5" | no beneficial effect |
| 1952 | Wells | ? | 25° angle blade | ? | early spring | ? | |
| 1957 | Mullin | white spruce | square spades | 2 | June and September | 3" | |
| 1957 | Stoeckeler and Jones | 2-0 jack pine | Barton root pruner | 1 | spring | 3-5" | highest survival with this method |
| | | 3-0 red & white pine | | | | | |
| 1958 | Shipman | longleaf pine | lifters | 1 | July, mid-season lot year | 7-8" | |
| 1958 | Stubbings | pines and eucalyptus | nursery designed pruner - wire | 1-3 weeks or 1 month until outplanting | initially when seedling is 5-6" tall | ? | |
| 1959a | Shoulders | longleaf pine | tractor drawn blade | 1 | 2-3 months before lifting | about 7" | good survival, most practical tech. |
| 1959b | Shoulders | longleaf pine | tractor drawn blade | 1 | late season | about 7" | good survival, most practical tech. |
| 1961 | Anonymous | all species | Gunn Lifting bar | 1 | March or September | 3-4" | almost as good as transplants |
| | | United Kingdom | Blair Atholl and Ledmore undercutter | | | | |
| | | Kenya - all species | piano wire | 3 week cycle | 9-11 weeks after sowing | 5-7" | failure to root prune courts failure when outplanting |
| | | Tanganyika | piano wire | | | | |
| | | Uganda | piano wire or knife | weekly | start 2-3 mo. before transplant | 4-5" | |
| | | N. Rhodesia coniferous tubed stock | piano wire or lifting tubes | every 3-4 weeks | start 6 weeks after pricking out | | |
| | | Nyasaland - potted and tubed stock | piano wire or lifting tubes | wire - 3-4 weeks weekly hand lifting | | | |
| | | Trinidad *Pinus caribaea* | cutlass | monthly | starts 3 mo. after transplanting | | |
| | | British Honduras - mahogany | spade | | when plants are 12" high | | |
| | | Sierra Leone | spade | once | 6-8 months before outplanting | | only done when surplus stock must be carried over |
| 1962 | Gingerich and Hertel | 2-0 Austrian pine | lifting bar | ? | before bud break | ? | |
| 1963 | Shoulders | longleaf, slash loblolly pine | tractor mounted blade | once | 1 month before lifting | 5-8" | recommendations for increasing survival |
| 1965 | Burgar | 1-0 jack pine | centre mounted lifter blade | once | before growth started in 2-0 year | 4" | no significant effect |
| 1967 | Dusek | information for 20 tree species | | | | | specifications are detailed in text of Dusek article on age depth etc. for each species |
| 1968 | Eis | Douglas-fir 1-0 | ? | once | early in spring | 5" | |

TABLE 3 Operational technique, equipment and brief results of root wrenching only.

| Year | Author | Species | Equipment | Frequency | Time of year | Depth | Comments |
|---|---|---|---|---|---|---|---|
| 1935 | Goudie | ? | sharp spade | | mid March | | |
| 1969b | Rook | Pinus radiata | ? | fortnightly over 5 mos. | ? | ? | high survival rate when transplanted under adverse conditions |
| 1969 | Van Dorsser | Pinus radiata | ? | fortnightly | ? | ? | fortnightly wrenched stock should be used for high, low, temperature and dry condition planting |
| 1977 | Bacon and Hawkins | Caribbean pine | horizontal reciprocating blade | fortnightly | 16 weeks prior to lifting - stock is 15-20 cm high | 12-13 cm | conditioning prescription for routine use |

TABLE 4 Operational technique, equipment and schedule of combined undercutting and root wrenching treatments. The specifications for the undercutting treatment in the top half of the table belong with wrenching treatment reported by the same author in the bottom half of the table.

| Operational technique | Year | Author | Species | Equipment | Frequency | Time of year | Depth |
|---|---|---|---|---|---|---|---|
| Undercutting | 1967 | Gleed | 1-0 Pinus radiata | piano wire between | 1 | height of seedlings usually Feb. | ? |
| | 1969 | Stockley | 1-0 Pinus radiata | Marsh reciprocating blade | 1 | min. height 6" usually March | ? |
| | 1970 | Moberly | 1.5-0 Pinus radiata | ? | 1 | | |
| | 1972 | Van Dorsser and Rook | radiata pine | reciprocating undercutter wrencher drawn by tractor | 1 | height of 10-12" midsummer | 2.5-3" 5-8 cm |
| | 1974 | McKinnon and Nicholson | radiata pine | ? | ? | late Nov. - autumn, late Feb. - spring | ? |
| | 1974 | Tanaka et al. | 2-0 Douglas fir | horizontally mounted 1/10" thin, 1" narrow blade 2 blades - tractor | 1 | late April | 6" |
| | 1978 | Shea and Armstrong | South eastern Queensland | | | | |
| | | | Caribbean pine | ? | 1 | when seedlings are 15-20 cm tall | 13-15 cm |
| | | | Bowenia Caribbean pine | ? | 1 | when seedlings are 10-15 cm tall | 13-15 cm |
| | 1984b | Bunting & McLeod | 2-0 red pine | ? | 1 | July 10th | 5-8 cm |
| | 1984 | Davey | ? | sharp flat blade | 1 | when seedlings attain height of 15 cm | 15 cm |
| Wrenching | 1967 | Gleed | 1-0 Pinus radiata | conventional blade tractor mounted | 4-5 times prior to lifting | ? | ? |
| | 1969 | Stockley | 1-0 Pinus radiata | Marsh reciprocating blade | ? | April | ? |
| | 1970 | Moberly | 1.5-0 Pinus radiata | ? | fortnightly | ? | ? |
| | 1972 | Van Dorsser and Rook | radiata pine | reciprocating undercutter wrencher - tractor | weekly, biweekly, monthly | midsummer or | 5-8 cm (just below undercutting depth) |
| | 1974 | McKinnon and Nicholson | radiata pine | ? | fortnightly | ? | ? |
| | 1974 | Tanaka et al. | 2-0 Douglas fir | 20-30° angle mounted 3/16" thicker, 2.5" wider blade | weekly | May or | 6" |
| | 1978 | Shea and Armstrong | South eastern Queensland | | | | |
| | | | Caribbean pine | ? | monthly | ? | 13-15 cm |
| | | | Bowenia Caribbean pine | ? | weekly | ? | 13-15 cm |
| | 1984b | Bunting & McLeod | 2-0 red pine | ? | every 3 weeks | July - October | 5-8 cm |
| | 1984 | Davey | ? | vibrating blade tilted upward at 15° angle | one or two passes through bed | final wrenching 1 month before lift | 15 cm |

For those requiring specifications for equipment, we recommend that the original publications be consulted. The intricacies of the operational practices should also be obtained directly from the literature.

One of the most thorough approaches to the discussion of equipment design is given by Lowman (1973) with reference to the redesign of a horizontal root pruner.

## GENERAL MORPHOLOGY

The morphological manipulation of seedlings by undercutting is based upon the physical removal of roots and the subsequent moisture stress hormonal inbalance. Riedacker (1976) determined that undercutting shortly after germination was most efficient at creating significant changes in the morphology of the root system of hardwoods. However, undercutting is most frequently used later in the seedling growing cycle. Olson (1930) recognized that underground root pruning could not fully replace transplanting because of variable seedling densities. Darby (1962) made the point that root pruning is just another of many valuable tools available to the nurseryman for modifying morphology and should be considered in combination with other important nursery variables such as drainage, nutrient levels, good seed selection, seedbed density and mulching.

Wrenching, used alone or in some combination with undercutting, is thought to influence moisture or hormonal stress by disturbing root to soil contact without necessarily removing large quantities of roots. Alteration of top growth or root form are attributed to these stresses. Correct timing of undercutting and wrenching treatments is essential to achieve the desired changes in morphology (Aldhous 1972, Cleary et al. 1978).

### Height growth

Control of height growth is a major objective of combined root pruning and wrenching at many nurseries. This is particularly true for the faster growing coniferous species from temperate climates.

Wrenching alone was very effective at halting height growth of radiata pine (Cameron 1969a, Benson and Shepherd 1977, Bacon 1979) as was undercutting followed by wrenching (Rook 1971, Van Dorsser and Rook 1972, Escobar et al. 1977a). The largest reductions in height were effected by the most severe or frequent treatments (Bacon 1979, Benson and Shepherd 1977, Cameron 1969a, Rook 1971, Van Dorsser and Rook 1972). Reductions in height growth of 27-35% were achieved by Escobar et al. (1977a).

Wrenching alone or combined undercutting and wrenching was equally effective at reducing shoot length of Caribbean pine (Bacon and Hawkins 1977, Bacon and Bachelard 1978, Bacon and Hawkins 1980), red pine (Bunting and McLeod 1984c), loblolly pine (Dierauf and Olinger 1982), Douglas fir (Tanaba et al. 1974, Koon and O'Dell 1977, Edgren 1978, Duryea 1981, Duryea and Lavender 1982, van den Driessche 1983, Hobbs et al 1987), white spruce and white pine (Mullin 1966) and oak (Rohrig 1977). In most cases height growth was interrupted immediately at the time of wrenching.

Bunting and McLeod (1984a,b) attributed the absence of reduction in height growth in red pine to initiating pruning and wrenching too late while Eis and Long (1972) saw no effect of vertical pruning or sidecutting

alone on Sitka spruce and western hemlock regardless of the month the treatment was carried out. Faulkner (1953) suggested that deep pruning Corsican pine at a depth of 11.5 to 14 cm (4.5 to 5.5 in.) was ineffectual at controlling height growth whereas root pruning at a depth of (3.5 in). 9 cm reduced the growth of the shoot. Single deep root pruning treatments (18 cm) regardless of date was ineffectual at eliminating unwanted late season height growth of loblolly, slash and longleaf pine (Shoulders 1960). Retardation of height growth may only be transient following a single August wrench of Douglas fir seedlings (Stein 1984), the treated stock eventually caught up to the unwrenched controls in the same growing season.

Undercutting followed by repeated wrenchings is an effective method of reducing height growth of most conifer seedlings provided that both treatments are not too deep. Control over the amount or extent of growth reduction can be exerted by adjusting frequency of wrenching, depth of pruning and wrenching, timing of treatment initiation with respect to the phenology and the number of treatments applied.

Seedling mass

Seedling mass is a good indicator of the assimilative efficiency of a plant. Treatments which alter the biomass of groups of seedlings do so by altering the physiological processes involved in growth. On a more practical basis, seedling size is often treated as being synonymous withvigour.

Undercutting alone reduced the shoot mass of Paulownia sp. (Beckjord 1982), western hemlock (Morris 1979), Austrian pine (Gingerich and Hertel 1962), jack pine (Burgar 1965) and oak (Röhrig 1977) although Ghosh et al. (1974) indicate an increase in shoot weight after root pruning Pinus patula. However, Mullin (1966) found no significant differences in total plant dry weight after pruning white pine and white spruce. This lack of effect reported by Mullin (1966) may have been due to his procedure which more closely resembled what we define as wrenching and to the fact that each treatment was followed by four hours of watering.

It is obvious from the literature that the mechanical process of undercutting itself varies substantially among the various pieces of equipment used. However, significant reductions in seedling mass can be achieved by undercutting even without a formal root wrenching procedure.

When undercutting is combined with root wrenching or when root wrenching alone is used, the general trend is also towards a reduction in total dry weight. Combinations of wrenching and pruning reduced the weight of radiata pine (Cameron 1969a, Rook 1971, Benson and Shepherd 1977, Nambiar et al. 1979), Caribbean pine (Bacon and Hawkins 1977) and red pine (Bunting and McLeod 1984a,b,c). Reduction of mass was primarily accounted for by the lack of shoot growth, while root size was largely unchanged or exhibited only slight decreases. Reductions in the mass of pruned and wrenched Douglas fir seedlings were observed by Stein (1984), Koon and O'Dell (1977), Edgren et al. (1978), Tanaka et al. (1976) and Duryea (1981), while Edgren (1975) observed an overall increase in seedling mass. Inconclusive results of dry weight changes resulting from pruning and wrenching Douglas fir were observed by Tanaka et al. (1975) and van den Driessche (1983).

Stein (1978, 1985) reported gains in root mass with wrenching but no total seedling weights were reported. Gains in root mass reported by other authors were countered by reductions in shoot mass resulting in a net reduction of seedling dry weight.

Much of the variation in response of dry weight to undercutting and wrenching was due to variations in technique or scheduling. These factors should be more clearly identified.

Root fibrosity

One of the most sought-after effects of root wrenching and undercutting was the production of abundant vigorous roots of small diameter instead of a large tap root or several large roots which are frequently broken during lifting or deformed during planting. A well formed, plantable root system should provide better water absorption and increased field survival.

The fibrosity of the root system of pruned or wrenched trees wasgreater than that for unwrenched Paulownia tomentosa (Beckjord 1982), radiata pine (Cameron 1969a, Rook 1971, Van Dorsser and Rook 1972), black walnut (Williams 1972), Douglas fir (Tanaka et al. 1974, Koon and O'Dell 1977), Scots pine (Parviainen 1982), Sitka spruce and western hemlock (Eis and Long 1972). Eis (1968) suggested that seedlings with poorly developed root systems responded more favourably to undercutting and sidecutting, and replaced several roots more readily, than seedlings that had good, well distributed root systems to begin with. He also emphasized the role of side or lateral pruning in producing compact and fibrous root systems. However, Venator (1983) did not observe additional lateral roots produced within the first 15 cm of the tap root of longleaf pine by sidecutting alone.

Undercutting is particularly effective at severing the tap root and producing a more fibrous root system in black walnut (Williams 1972), yellow poplar (Thor 1965), and other hardwoods (Riedacker 1976). A more heavily branched root system in hardwoods can be produced by undercutting the tap root very soon after germination (Riedacker 1976). Other root system modifications such as those produced by mycorrhizae can also be enhanced by root cutting (Göbl 1966).

Despite the encouraging results of Van Dorsser and Rook (1972) where conditioned seedlings produced a fine, compact root system by pruning and wrenching, other workers have tried but failed to demonstrate this success in other species. Reduced tap root weights with no change in lateral root weights or total root weights were observed with wrenched Douglas fir seedlings (Duryea 1981, Duryea and Lavender 1982, and Hobbs et al. 1987) although the procedure reported by Hobbs et al. (1987) was an undercutting procedure which more closely resembled wrenching. This may or may not be interpreted as increased root fibrosity. Ponderosa pine, on the other hand, responded to undercutting with reduced weights of tap roots and lateral roots (Hobbs et al. 1987). Loblolly pine did not increase the mean number of roots, an index closely related to fibrosity in response to a combined pruning and wrenching treatment (Venator and Mexal 1981). Root fibrosity is difficult to measure and quantify and therefore, remains primarily a subjective parameter.

The location of stimulated root growth is important, but has been considered by very few workers. Wilcox (1955), in a study of root regeneration of noble fir reported that root regeneration was primarily in the proximity of the cut surfaces and that pruning did not result in larger

numbers of laterals along the length of the roots. Therefore, root system modifications may better be described by branchiness as opposed to fibrosity.

Variability exists in how root fibrosity responded to undercutting and wrenching, but this appears to be largely due to the variety of experimental procedures and species used. The success of root modification appears to depend heavily upon the timing of the undercutting; i.e. after germination (Riedacker 1976) as opposed to treatment in the second or third year. Root modification can be more easily induced at an early stage. However, the severity of the treatment, amount of stress endured by the seedling and the frequency of the treatment application plays a major role in increasing root fibrosity (Cameron 1969a, Van Dorsser and Rook 1972).

Stem or root collar diameters

The effects of undercutting, wrenching or lateral pruning on stem diameter are dependent not only on the treatment applied but seedling phenology at the time of application.

Inconsistent results were obtained for Douglas fir, with some authors reporting no change in diameter with wrenching (Edgren 1975, Tanaka et al. 1976, Stein 1984) and others reporting small but significant reductions (Tanaka et al. 1974, Koon and O'Dell 1977, Edgren et al. 1978, Duryea 1981). These inconsistencies can probably be explained by the relative plasticity in growth of Douglas fir and by variations in technique and timing of treatments. Generally the most frequent and most severe treatments produced the largest reductions in seedling diameter. Stein (1978) noted that the diameter of wrenched seedlings tended to be smaller shortly after treatment but little difference in size was observed at the end of the growing season.

A similar conflicting response of loblolly pine to undercutting and wrenching was reported; some with no diameter reduction (Shoulders 1963, Venator and Mexal 1981) and others with a reduction in diameter (Tanaka et al. 1976, Dierauf and Olinger 1982). Reports of work with radiata pine indicated an increase in variability in diameter (Bacon 1979) or a reduction in diameter with wrenching (Benson and Shepherd 1977, Rook 1971). This increase in variability could reduce the ability to detect significant differences between treatments.

No significant reduction in stem diameter was observed undercut white spruce (Mullin 1966) or with red pine wrenched at 10-15 cm (Bunting and McLeod 1984a). However, other work by Bunting and McLeod (1984b,c) showed a significant reduction in stem diameter of red pine with a more severe pruning and wrenching treatment.

Undercutting and root wrenching will reduce the stem diameter of treated seedlings provided the treatment is of sufficient duration and severity. This may imply reduced quality if stem diameter is correlated with the ability to survive or perform well in the field. However, reduced diameters are not always the outcome of wrenching or pruning and are not necessarily detrimental if other stock characteristics are enhanced.

Top-root ratio

Top-root ratio or the general balance of the tree is also frequently expressed as the root-shoot ratio but for reasons of consistency, only the top-root ratio will be used in this discussion.

There are few examples of top-root ratio increasing with undercutting and wrenching. Ghosh et al. (1974) noted increases in top-root ratio of germinant Pinus patula seedlings prior to transplanting. Röhrig (1977), on the other hand, had larger top-root ratios on oak sedlings pruned in July than for earlier prunings. In both cases root regeneration was not adequate to recover the lost roots. Stein (1984, 1985) demonstrated increased top-root ratios in Douglas fir seedlings wrenched early in the season. However, this difference was not maintained later in the growing season. None of the cases of increased top-root ratio was indicative of long term changes in tree balance.

Several papers have been inconclusive in linking changes in top-root ratio to undercutting and wrenching. Burgar (1965) found no effect on the balance of jack pine as did Mullin (1966) with red pine. However, undercutting depth in these trials was relatively shallow. Also, no response in top-root ratio was observed in Douglas fir and ponderosa pine (Edgren 1975) when undercutting was done at 10-15 cm and wrenching was done at 15-20 cm. Dykstra (1974) also observed little or no change in top-root ratio when 6-week-old seedlings were undercut at 3 depths. Undercutting too shallow may remove too many roots and too deep may have no effect; both treatments having the effect of maintaining high top-root ratio.

The majority of literature on undercutting and wrenching of nursery stock that deals with top-root ratio has demonstrated that these cultural treatments decrease top-root ratio. Repeated wrenchings of radiata pine were effective at reducing top-root ratio (Rook 1971, Rook 1969b, Cameron 1969a) and were most effective when wrenching occurred soon after the undercutting treatment (Escobar et al. 1977a) or when wrenching was more frequent (Rook 1971).

Douglas fir responded favourably to most undercutting and wrenching treatments by reducing the top-root ratio and thus improving the balance of the tree (Tanaka et al. 1974, Tanaka et al. 1976, Koon and O'Dell 1977, Stein 1978, Duryea 1981, Lupke 1981, Duryea and Lavender 1982, van den Driessche 1983, Duryea 1984, Stein 1984,1985). A similar plasticity in top-root ratio was also observed in Caribbean pine (Bacon and Hawkins 1977, Bacon and Bachelard 1978, Bacon and Hawkins 1979, 1980, Mahmood 1983), yellow poplar (Sluder 1964), Corsican pine (Atterson 1964), Austrian pine (Gingerich and Hertel 1962), western hemlock (Morris 1979), red pine (Bunting and McLeod 1984a,b) and in pine varieties grown in Finland (Parviainen 1981).

The evidence suggests that top-root ratio can be effectively controlled by undercutting and root wrenching. Top-root ratio is most effectively modified by more severe treatments which restrict shoot and foliage growth.

**ROOT REGENERATION**

Root regeneration is essential to plantation establishment or the continuing vigour of seedlings in the nursery. This is especially so after undercutting or wrenching. Wilcox (1955) observed that pruned roots of noble fir regenerated new roots within 20-30 days of planting and that these new roots were concentrated near the pruned surfaces. Wrenching had little effect on first order roots of transplanted radiata pine but increased the

number of third order lateral roots after transplanting (Nambiar et al. 1979) and second and third order laterals (Rook 1971). Greater development of second and third order roots of Corsican pine after outplanting has also been observed (Aldrich-Blake 1930, Faulkner 1953).

In the nursery, root regeneration is largely influenced by the timing of the pruning treatment. Douglas fir seedlings pruned in June developed new roots best while July pruning was less successful and the regeneration of roots pruned in August was almost non-existent (Eis 1968). This work was further supported by Eis and Long (1972) who suggested that roots of western hemlock and Sitka spruce pruned late in the growing season formed callus tissues around the wound from which new roots developed the following spring.

Undercut and root wrenched radiata pine seedlings had roots with higher relative growth rates and lower levels of inhibitors per unit of root weight than non-treated seedlings (Sweet and Rook 1972). This could help to explain the larger capacity for root regeneration of Caribbean pine seedlings wrenching on a weekly basis than on a monthly basis (Bacon and Bachelard 1978). They suggested that this greater capacity for root growth must be an intrinsic factor in determining their superior survival after outplanting.

Root regeneration is also largely influenced by abiotic factors. Nambiar et al. (1979) noted the importance of suitable soil temperature in the success of root wrenching to initiate new root growth of radiata pine. Soil temperature affected the initiation of new lateral primordia and elongation, branching, thickness, weight and morphology of the new roots. The largest root regeneration potentials after root pruning of Caribbean pine was observed at soil and air temperature of 25-30°C (Abod et al. 1979). The proliferation of old roots, rather than initiations of new roots predominate at lower soil temperature. Radiata pine regenerated roots best at 20-30°C, and soil temperature directly influenced root texture and morphology as defined by relative abundance of coarse and fine roots (Stupendick and Shepherd 1979). The peak of root regeneration activity occurred from the 16th to the 20th day after root pruning (Stupendick and Shepherd 1980). Therefore, temperature should be considered in planning pruning and wrenching treatments to maximize fine-textured root growth.

The parameter of root growth potential or root growth capacity is not necessarily increased by either undercutting or root wrenching. Van den Driessche (1983) observed that Douglas fir root growth capacity was not significantly influenced by wrenching and that lifting date had a more important affect on root growth capacity which in turn influenced survival. Abod and Sandi (1983) actually observed reduced root growth capacity of Caribbean pine after combinations of restricted watering and root pruning. They also suggest that root growth capacity values alone are an insufficient basis for predicting field survival because in many situations low root growth capacity may depress transpiration without affecting the plant survival. These findings are supported by Feret and Kreh (1986) who suggest that root growth potential is affected primarily by physiological factors not modified by undercutting.

## DENSITY AND SPACING

One of the reasons for the success of transplants as opposed to seedling stock is the uniform and reduced spacing of the trees within the nursery beds. The importance of seedling density and uniform spacing has also been recognized for the success of undercutting or wrenching treatments.

Olson (1930) recognized that despite the development of satisfactory underground root pruning devices, transplanting would continue to be the most practical means of modifying the root system of yellow pine and western larch until a more uniform spacing of plants could be achieved by direct seeding. Huberman (1940) verified the importance of seedling density to slash, longleaf and shortleaf pine and recognized density as having a larger influence on root development than undercutting itself.

Fertilizing and root pruning longleaf pine seedlings was most effective at a density of 20 seedlings per square foot (Johansen 1955) and this density produced larger and more vigorous seedlings than at a density of 40 per square foot (Shipman 1958). However, Shoulders (1959b) found no difference in performance between longleaf pine grown at densities of 18 and 27 per square foot.

Douglas fir responded similarly, with best survival at densities of 11-17 per square foot (Anonymous 1961). These results were confirmed by Menzies (1980) in recognizing that seedlings grown at the lower densities were sturdier. The strongest seedlings, those raised at a low density, will also give the best results in a plantation (Michaud 1984).

Optimal spacing must be related to species, age class, climate and nursery soils (Chavasse 1978a). Jakabffy (1969) suggested that to be successful, the root pruning technique requires that sowing be sparse and even. He suggested that special seeding techniques be used to improve density control. Seedling density of radiata pine should be adjusted to suit the final height of the planting stock being produced (Van Dorsser and Rook 1972). Seedling spacing of 1.25-6.5 x 17.5 cm did not alter height growth but produced wider, heavier, stockier plants with significantly greater amounts of lateral fibrous roots. Chavasse (1978a) reduced radiata pine cull rate from 28% to 4%, improved survival after outplanting from 85% to 96% and achieved an increase in first year growth by producing a regular 7 cm square spacing. Tinus (1981b) also recommended a 7 cm square spacing of radiata pine for implementing box pruning. This can be achieved with a precision seeder or by hand thinning (Tinus 1981a). He suggested that a mechanical thinner is required to produce such a spacing.

Van Dorsser (1981) summed it up well by stating that since undercutting and wrenching reduces diameter growth as well as height growth, it is important to allow seedlings sufficient individual space for maximum diameter growth.

Undercutting and wrenching should be used along with other nursery cultural techniques such as regulating seedbed density to achieve best and most economical results. There is no evidence to suggest that undercutting or wrenching are as effective at higher seedbed densities.

## HORMONAL RESPONSE

The hormonal response of seedlings to undercutting or wrenching may be every bit as important as drought stress in producing conditioned seedlings (Rook 1972). Rook (1972) attributed the better planting stock obtained from shallow, as compared to deep, undercutting to the removal of a larger number of root tips rather than a greater water stress. The absence of detectable cytokinin activity in root disturbed trees would suggest a cause for the reduction in shoot development (Morris 1979) as would be necessary for the adjustment of shoot and root balance. Sweet and Rook (1972) deduced that the reduced level of growth inhibitor (ABA) in the conditioned root (relative to the control root) is associated with a greatly increased relative growth rate. Their data indicate that levels of inhibitor rather than levels of promoter influenced the changes in growth pattern resulting from conditioning. Bacon and Bachelard (1979) concurred in this general finding but attributed the lack of inhibitor to a reduced capacity for inhibitor synthesis. Little evidence of a causal correlation is presented.

Short term changes in auxin activity have also been observed as a response to root pruning (Carlson and Larson 1977). The immediate, short lived auxin peaks after disturbance could indicate that auxin participates in "triggering" root primordia initiation. Carlson and Larson (1977) also observed an increase in cytokinin activity in root xylem sap 24 hr after pruning and suggested the source could be the wounded or pruned tissue itself rather than the root tips. The increase in cytokinin activity can be attributed primarily to the effects of water stress (Bacon and Bachelard 1979).

Gibberellin activity was reduced by various stock conditioning treatments with the magnitude of reduction directly related to the magnitude of the disturbance (Bacon and Bachelard 1979). This could be attributed to either a reduction in gibberellin synthesis sites in the root tips or to a reduction in the plant water status. Bacon and Bachelard (1979) favour the later explanation.

Some extrapolation can be made to nursery stock from research into the effects of root pruning of older trees, primarily for the purpose of flower stimulation. Early work by Stephens (1964) found root pruning ineffective at stimulating flowering. However, Fraser (1976) and Ross et al. (1985) found that root pruning was effective for this purpose. Ross et al. (1985) also noted that root pruning was more effective than a gibberellin treatment at inducing flowering. This suggests an overall hormonal response to pruning which, as yet, has not been fully explained.

Most work with hormonal response has concentrated on short term benefits rather than examining the long term changes in growth patterns. Fraser (1976) noted the increases in number of cones the first year after root pruning 7- and 8-year-old white and black spruce, but the number decreased later when the effect of reduced tree vigor due to root pruning became evident. We think this may be a veiled warning on the consequences of reducing tree vigour through pruning and thereby reducing the ability of a seedling to cope with stressful sites.

## NUTRIENT RELATIONS

The two most common observations of nutrient relations with respect to root pruning and wrenching are the development of chlorosis and a diversion

of photosynthate to the roots after a disturbance. Early work by Rook (1969a) showed that wrenching caused a yellowing of foliage and a reduction in chlorophyll a and b and in carotenoids. Benson and Shepherd (1977) attributed this chlorosis to a general reduction in foliar nitrogen and phosphorous with increasing wrenching severity of radiata pine but failed to show an influence on field survival or subsequent growth. Reduction of N, P, K and Mg in undercut oaks was also observed by Röhrig (1977). Menzies (1980) noted that wrenched Douglas fir seedlings also had lower mineral nutrient level of N, P and K and lower chlorophyll content of the foliage than seedlings from a control treatment. Reductions in foliar nutrient content could be attributed to reduced foliar uptake of N, P and K due to wrenching (van den Driessche 1983). Fertilization significantly increased needle concentrations of these nutrients in wrenched stock. Therefore, the role of fertilizer applications to alleviate chlorosis due to wrenching should be considered.

Food reserves were expected to change in response to the reduction in growth due to wrenching but Rook (1969a) detected no significant differences in food reserves among tissues. However, he observed that starch levels in the roots of frequently wrenched seedlings were lower than in unwrenched seedlings. Rook (1971) also noted that undercutting and wrenching radiata pine seedlings biweekly caused a threefold increase in the relative flow of $^{14}C$-assimilates from the foliage to the roots when compared with the control. Bacon and Bachelard (1978) also observed a decrease in pigment concentration in wrenched plants as well as an increased translocation of $^{14}C$-assimilate to the roots of treated Caribbean pine. Roots of wrenched Caribbean pine seedlings showed a general increase in starch content (Abod and Sandi 1983) and insoluble nitrogen (Coker 1984) with increasing severity of wrenching. Coker (1984) noted an increase of insoluble nitrogen in lateral roots prior to increased dry weight. He concluded that regenerating root systems form a strong "sink" for both photosynthate and nitrogen mobilized from other parts of the plant.

Conflicting views of the role of nutrient manipulations in eventual field performance are presented by McCracken (1979), who claims that carbohydrate concentration per se is not a feature of the improved survival of wrenched mugo and radiata pine seedlings; and Menzies (1980), who claims that the higher proportion of nonstructural carbohydrate in the finer roots of Douglas fir could contribute to higher root regeneration potential and root activity. The effect of root wrenching on nutrient relations is no doubt complex and has only been touched on in the literature available to date. Much more work is required to understand the implications of nutrient relations to the cultural practices of wrenching and undercutting.

## FERTILIZER APPLICATIONS

Modifications to fertilizer schedules have been suggested by many researchers, but the most obvious use of fertilizers is to offset the chlorosis developed in root pruned seedlings. Stockley (1969) noticed this loss of colour in 1-0 radiata pine. Van Dorsser and Rook (1972) found that applying nitrogen not only checks the loss of chlorophylls but also builds up nitrogen reserves, especially in the roots. Menzies (1980) suggested a

late season application of N, P and K to alleviate the symptoms of chlorosis. Aldhous (1972) recommended that the appropriate nutrient should be applied as a top dressing to combat any nutrient deficiency as detected by needle size or colour. Close monitoring of the nutrient concentrations of wrenched seedlings was recommended by Tanaka et al. (1974) to permit prompt addition of nutrients as required.

Fertilizer amendments may even be combined with undercutting and wrenching to produce quality radiata pine suited for outplanting under stressful conditions (will et al. 1971). Liberal quantities of fertilizers should be supplied to ensure adequate supplies of nutrients while wrenching and undercutting are used to suppress top growth.

Application of a well balanced fertilizer at the time of sowing and 11 weeks after sowing radiata pine resulted in less needle death and a slight increase in dry weight at the end of the growing season (Benson and Shepherd 1977). Increased external supply of nutrients can also contribute to increased root stimulation of root wrenched radiata pine seedlings (Nambiar et al. 1979). High nitrogen combined with root pruning also produced superior survival for yellow poplar (Thor 1965). However, increasing fertility can reduce cold hardiness while at the same time increasing root growth capacity (van den Driessche 1983).

Obviously a successful root wrenching and pruning program must include the consideration of a modified fertilization schedule. However, this complex issue is far from being fully understood. Caution is advised.

**STORAGE**

Prolonged storage of bare root nursery stock is a fairly recent phenomena. The success of cold storage is largely influenced by the physiological state of the seedlings at the time they are put into storage as well as by the storage environment. Van Dorsser (1969) first refered to the advantage of using frequently wrenched stock to achieve the best results from cold storing radiata pine. Van Dorsser and Rook (1972) went so far as to suggest that cold storage is a good means of testing how well radiata pine have been conditioned. They attribute this increased tolerance to storage to the higher starch content in wrenched seedlings.

Tanaka et al. (1974) noted an increase in frost hardiness of undercut and wrenched Douglas fir seedlings as tested by 2 hours freezing at -10°C. Wrenched seedlings sustained less injury. They also suggested that undercutting and wrenching accelerated dormancy and cold hardiness. Also, stored, wrenched radiata pine recovered more quickly after outplanting than stored unwrenched stock (McCracken 1978, 1979) but he deimphasized the role of carbohydrate concentrations in this effect.

Mullin and Hutchison (1979) noted that root pruning increased survival of red pine after 5 months of frozen storage as did Bunting and McLeod (1984a). However, these findings were not confirmed by Duryea and Lavender (1982) with Douglas fir stored for 2 months at 2°C. Van den Driessche (1983) on the other hand, found that wrenching advanced the date at which Douglas fir seedlings were ready for storage, but he found no increase in frost hardiness.

There appears to be a definite need for developing a pruning or wrenching schedule to facilitate overwinter or prolonged cold storage of bare root stock. Much remains to be discovered on how the technique manipulates seedling physiology.

## DISEASES

It is generally acknowledged that trees under stress are more susceptible to disease and that wrenching and undercutting techniques put trees under stress, even if only temporarily. Excessive nutrient or moisture availability can also increase disease susceptibility. However, the influence of wrenching or undercutting on nursery stock diseases has been largely ignored.

Davey (1964) speculated that root disease organisms could invade seedlings through the cut roots but Petäisto (1982) failed to demonstrate any relationship between incidence of fungal infection and pruning. The only other evidence of interaction between disease and root pruning was reported by Bedker and Blanchette (1983) who observed that Nectria cinnabarina cankers closed more slowly on older honey locust trees subjected to stress imposed by root pruning.

Much more work is required in this area to determine if root wrenching or undercutting contributes to disease problems in bare root nurseries, and if so, how these diseases could be avoided.

## UNDERCUTTING AS A SALVAGE TECHNIQUE

A problem which was more prevalent in the past than now is the holding of unlifted seedlings for an additional year without letting them get too big. Olson (1930) played down the role of undercutting as a substitute for the more expensive operation of transplanting because broadcast seeding does not give a uniform spacing of plants. Instead, he suggested undercutting for holding down the size of stock which could neither be transplanted or shipped. A similar philosophy was developed by Stubbings (1958) in southern Rhodesia. Dusek (1967) and Aldhous (1972) provide more recent documentation of this practice. However, in this age of rapid reforestation, holding stock for an additional year is not generally a problem, except possibly for small private nurseries.

## BOX PRUNING

Brunsden (1981) provide a good description of a box pruning procedure to produce radiata pine with a root system which would be difficult to "screw up" in the planting hole. The first step is to use precision sown seed or thin beds to a density of 10 cm x 10 cm. When seedlings are 20 cm high, a reciprocating blade is used for undercutting at a depth of 15-18 cm. Four weeks after undercutting, box prune to a depth of 12-15 cm at a distance of 5 cm from the seedlings. The frequency of pruning depends on root regeneration, usually every 4-5 weeks and a total of 3 times. A shallow undercut (8-10 cm) 2 weeks prior to lifting is recommended. Chavasse (1978b) describes in detail, some of the implications of box pruning on Douglas fir.

The main benefits of box pruning were identified as superior stress resistance, reduced malformation of roots after planting and a reduced number of handling steps after lifting (Brunsden 1981). Chavasse (1978b) noted that box pruned radiata pine exhibited less root system distortion after outplanting, greater height and diameter growth over the first two growing seasons than normally wrenched seedlings and that the development of taproots and laterals was superior.

Box pruning also offers the unique property of eliminating root tangling and all of the damage that untangling causes (Tinus 1981a). However, an "across-the-bed" root pruner necessary for box pruning and a suitable mechanical thinner are not yet available. Precision seeding technology that would be suitable for box pruning is also not yet available.

Although this technique appears quite promising, little work has been done to quantify the benefits in relation to the technological developments required to make this technique operational in most bare root tree nurseries.

**ACKNOWLEDGEMENTS**

The authors would like to thank A. Chalk and J. Addy for their assistance in locating the pertinent literature and to J. Tonge and D. Lennox for their assistance in typing. S. Watson provided valuable assistance in compiling the indices.

1. Abbott, H.G. and S.D. Fitch. 1977. Forest nursery practice in the United States. J. For. 75: 141-145.

   In 1974, 99 out of 134 forest nurseries in the United States responded to a questionnaire. Information was collated on species, seed procurement, seedling culture, lifting, shipping, production costs and research needs. The survey indicated that root pruning was practiced by two-thirds of the respondents.

2. Abod, S.A. and S. Sandi. 1983. Effect of restricted watering and its combination with root pruning on root growth capacity, water status and food reserves of Pinus caribaea var. hondurensis seedlings. Plant Soil 71: 123-129.

   Six-month-old Pinus caribaea var. hondurensis seedlings were subjected to various regimes of restricted watering and their combinations with root pruning to determine a suitable technique of producing seedlings with optimum physiological condition for successful bare-root planting in Malaysia. From the range of treatments tested, plants subjected to watering once every 9 days were found to be the "hardest" in terms of highest root growth capacity, leaf water content, root starch content and in having a moderately low transpiration rate. P. caribaea seedlings subjected to this preconditioning treatment may be more able to survive bare-root planting. Conditioning stock by root pruning combined with watering treatments was not as effective as the watering regime alone.

   (edited authors' abstract)

3. Abod, S.A., K.R. Shepherd and E.P. Bachelard. 1979. Effects of light intensity, air and soil temperatures on root regenerating potential of Pinus caribaea var. hondurensis and P. kesiya seedlings. Aust. For. Res. 9: 173-184.

   Experiments were carried out to investigate the effects of light intensity and air and soil temperature on the root regenerating potential after root pruning of Pinus caribaea and Pinus kesiya seedlings, in order to develop optimum cultural practices. An increase in light intensity from 16 to 50% of full sunlight increased root regenerating potential markedly, but a further increase to full sunlight had little effect; even slightly reducing regeneration. Partial shade may be more beneficial than full sunlight when new roots are being initiated after root pruning. Both air and soil temperature markedly influenced root regenerating potential, with soil temperature having an effect independent of air temperature. Negligible root regeneration took place with either species at soil temperatues of 15°C and below. Optimum root regeneration after root pruning occurs at air and soil temperatures between approximately 24 and 30°C. The maximum response involves the elongation of all or nearly all existing old roots, but more importantly, a massive proliferation of new root initials.

   (authors' abstract)

4. Aldhous, J.R. 1972. Transplanting and undercutting. p. 76-85, plates 19-21. In Nursery practice. G.B. For. Comm. Bull. No. 43. 184 p.

   The concepts of undercutting, root pruning and wrenching are discussed with respect to their role in nursery practice.

Physiological and morphological effects are presented as well as economic benefits. Procedures are outlined for undercutting, pruning and wrenching.

5. Aldrich-Blake, R.N. 1930. The effect of disturbance on the balance of the plant. p. 28-36 In R.N. Aldrich-Blake (ed.). The plasticity of the root system of Corsican pine in early life. Oxford Forestry Memoirs No. 12.

   A 1930 study comparing the value of undercutting with transplanting of Corsican pine (Pinus laricio var. corsicana), showed no advantage to either method. Both treatments checked top growth but increased tertiary root growth. Pruning secondary roots produced increased tertiary root growth.

   Root pruning was done by a single horizontal cut at a depth of 7-9 inches to sever the radicle only or by a series of cuts in the shape of a cone, 7 inches deep and 5 inches in diameter.

6. Anderson, E.D. and A.M.C. Jolley. 1975. Combination seedbed raiser/lateral root pruner. Forest Industries Review 6 (11): 11, 13.

   Engineers at the New Zealand Forest Service, Rotorua conservancy have designed a rear mounted machine to be used in the nurseries for raising, forming and compacting seedbeds in one simple operation. A rolling coulter, lateral root pruning attachment for this machine is described.

7. Anonymous. 1942. Root pruning - a labor saver. USDA Lake States Forest Experiment Station. Tech. Notes No. 190. 1 p.

   In 1942, root pruning was recommended as a labor-saving technique for use in seedbeds to eliminate transplanting of some stock types. The best type of root pruning consists of running a horizontal blade under the trees at a depth of 4 to 5 inches and a vertical blade between the rows. Results of pruning tests on spring planted red pine Pinus resinosa Ait.) and white pine (Pinus strobus L.) 3-0 seedlings had survival percentages of 82-97 for red pine and 75-98 for white pine. It was recommended that seedlings be fertlized 1 to 4 weeks after root pruning.

8. Anonymous. 1961. Root pruning of nursery stock. In Forestry newsletter. The Forestry Adviser, Colonial Office, London. Appendix C. p. 1-8.

   The appendix to this newsletter summarized root pruning and undercutting of nursery stock in England, Wales and United Kingdom colonies in 1961. Frequency, age of seedlings, depth, species and equipment are described for each country. Root pruning is recommended in all areas.

9. Armson, K.A. and V. Sadreika. 1979. Forest tree nursery soil management and related practices. p. 35, 70-71, 95-97. Ont. Min. Natur. Resour. Queen's Park, Toronto.

   The available literature on root pruning and wrenching of Ontario stock is reviewed. It is noted that there is little or no information available on pruning and wrenching schedules for Ontario species. In describing second and third year treatments, wrenching

is included along with fertilizer, irrigation, pesticides and herbicides.

10. Atterson, J. 1964. Survival and growth of undercut seedlings in the nursery and forest. G.B. For. Comm. Rep. For. Res. 1963: 147-156.

Some forty nursery experiments, between 1951 and 1958, on a number of conifer and broad-leaved tree species, tested various depths and seasons of undercutting. Comparisons between undercut plants, transplants and undisturbed seedlings of the same age, failed to show any important differences in survival rates or growth in the forest attributable to the type of plant, except in one species. Corsican pine (Pinus nigra var. calabrica) transplants were superior to seedlings and undercut stock was intermediate in survial value. Treatment produced marked differences in what are usually considered to be important characteristics, transplants on average being "better balanced" and sturdier than seedlings and undercut stock intermediate in these respects. However, the differences in size of stock attributable to the treatment received in the nurseries in which they were grown were very much larger than those brought about by any of the experimental treatments.

(author's summary)

11. Bacon, G.J. 1979. Investigations into radiata pine establishment on the Queensland granite belt. A review of findings and the literature. Dep. For. Queensl. Res. Pap. No. 12. 75 p.

The Granite Belt environment, existing plantations and current establishment techniques are briefly described.

Local investigations into various aspects of radiata pine (Pinus radiata) establishment including nursery practices, site preparation techniques, refilling operations and grass competition control are discussed in detail. The associated literature is reviewed.

Seedlings subjected to root wrenching regimes at three intervals and two depths were examined for nursery height growth, root collar diameter and field survival and growth. Frequent root wrenching conditions stock to withstand transplanting stress. The most significant improvement in field performance is gained from intensive site preparation, particularly line ploughing. Other practices are shown to exert a real influence on initial seedling survival and growth, stock grading notably on a shoot length and root collar diameter basis, and root dipping into a clay slurry. Shoot topping and refilling operations cannot be recommended. Dalapon (2,2-DPA) is phytotoxic to recently planted radiata pine seedlings.

(edited author's abstract)

12. Bacon, G.J. and E.P. Bachelard. 1978. The influence of nursery conditioning treatments on some physiological responses of recently transplanted seedlings of Pinus caribaea Mor. var. hondurensis B. and G. Aust. For. Res. 8: 171-183.

The aim of this investigation was to quantify the effects of different root wrenching intensities (untreated controls, wrenched weekly and wrenched monthly) on some physiological processes in caribbean pine (Pinus caribaea Mor. var. hondurensis B. and G.) seedlings raised in a nursery and transplanted to controlled environments.

Measurements made on seedlings at or before routine lifting from the nursery bed showed that wrenching caused a transient (4 days or less) reduction in the relative water content of the leaves, induced partial closure of the stomata in treated stock, and altered seedling morphology; shoot size was reduced and the root/shoot ratio was increased.

After transplantation, measurements were made of transpiration, net photosynthesis, $^{14}C$ translocation of the root systems, and root-regeneration capacity, and in each instance the stock-treatment ranking was week > month > control. Stock survivals and height growth followed the same ranking.

The evidence points to the early development of a major water stress in mildly wrenched or unwrenched, i.e., non-conditioned, plants following lifting in the nursery, even though the roots were maintained in well-watered media. Consequently the stomata closed to a greater extent than in weekly wrenched stock, and gas-exchange rates fell accordingly. The maintenance of higher water potentials in conditioned plants implies that their root systems were better adapted to meet the transpirational demands of the shoots. A higher root/shoot ratio, and an initial condition of partial stomatal closure would assist this adaptation.

The results are consistent with those from survival studies made in the field.

(author's abstract)

13. Bacon, G.J. and E.P. Bachelard. 1979. Changes in growth substance levels associated with the conditioning of Pinus caribaea Mor. var. hondurensis B. and G. seedlings to water stress. Aust. For. Res. 9: 241-254.

Chromatographed methanolic extracts from both field- and phytotron-grown caribbean pine (Pinus caribaea Mor. var. hondurensis B. and G.) seedlings were tested in appropriate bioassays for the presence of gibberellin-, cytokinin-, inhibitor- and auxin-like activity. Activity associated with these classes of plant hormones was demonstrated and endogenous concentrations determined.

Stock conditioning by droughting and/or partial root severance in open grown seedlings and potted stock induced marked changes in the level of some growth substances. Gibberellin and cytokinin concentrations were significantly reduced in all pine tissues by treatment, while inhibitor levels were significantly increased. Auxin activity remained relatively constant in the root systems investigated.

Alterations in hormone concentrations are interpreted as responses by the plant to water stress. The magnitude of change was related to the degree of stock disturbance (i.e. stress) effected by each conditioning treatment. It is suggested that changes in the levels of growth substances are involved in the adaptation of seedlings of var. hondurensis to water stress.

(edited authors' abstract)

14. Bacon, G.J. and P.J. Hawkins. 1977. Studies on the establishment of open root Caribbean pine planting stock in Southern Queensland. Aust. For. 40: 173-191.

As an alternative to costly containerized planting stock, an inexpensive seedling conditioning regime was developed to permit successful planting of open root caribbean pine (Pinus caribaea Mor.) stock.

Trials were conducted at two coastal centres in Southern Queensland, Byfield and Beerwah. Initially stock were subjected to mild *in situ* root wrenching schedules (roots cut at a depth of 20 cm, maximum of three wrenchings) alone or in combination with a heeling-in treatment. These conditioning treatments proved too conservative. More intensive root wrenching regimes (less than 15 cm deep at weekly, fortnightly and monthly intervals over a 16 week period) were adopted. Frequent root wrenching stimulated lateral root development and reduced shoot growth in the nursery and gave acceptable stock survivals in the field over a range of planting conditions.

The conditioning prescription calls for fortnightly root wrenching with a horizontal reciprocating blade set at a depth of 12-13 cm, when stock reaches a height of 15-20 cm. Lateral root cutting using vertical blades is timed at six week intervals. Treatments should be operational for sixteen weeks prior to lifting. Root wrenching methods should be adjusted in more tropical areas.

(edited authors' abstract)

15. Bacon, G.J. and P.J. Hawkins. 1979. Intensive root wrenching: a prerequisite for the successful establishment of 1-0 *Pinus caribaea* Mor. seedlings. U.S. For. Serv. Tree Plant. Notes 30 (1): 5-7.

A trial was conducted to evaluate the frequency of root wrenching as a preconditioning technique on 1+0 *Pinus caribaea* Mor. seedlings. Weekly and bi-weekly wrenchings by hand, using a flat bladed spade produced larger root/shoot ratios and better field survival than monthly wrenchings. A bi-weekly wrenching schedule at 13 cm depth, combined with vertical pruning is recommended after seedlings attain a height of 15 to 20 cm.

16. Bacon, G.J. and P.J. Hawkins. 1980. Establishment trials with *Pinus caribaea* var. *hondurensis* in southeast Queensland. Malays. For. 43: 24-36.

Two kinds of caribbean pine (*Pinus caribaea* Mor. var. *hondurensis* Barr. and Gold.) planting stock were evaluated in separate trials conducted at Beerwah, Queensland. In one trial, seedlings were raised for various periods in 5.7 cm square compressed peat pots before transferring to the planting site. Height and biomass development of the seedlings improved the longer the seedlings were held in pots at the nursery. In the other experiment seedlings, grown in nursery beds, were subjected to different root wrenching schedules and transplanted open root to the field. The wrenching procedure was to cut the tap root at a depth of either 7.5 cm or 15 cm on both sides. The intervals between wrenchings were weekly, bi-weekly and monthly. The best results were obtained with deep root wrenching on a weekly basis.

17. Baker, L.A. 1961. Knife-type lateral root pruner. U.S. For. Serv. Tree Plant. Notes 46: 17-18.

Two types of rolling coulter lateral root pruners were found to be unsatisfactory for use in Oregon State forest nurseries. In 1960, a knife-type lateral root pruner was constructed and tested. It was found that the knife-type pruner could root prune all the seedbeds in one-third of the time that the coulter-type pruner took, with very little soil compression.

18. Beckjord, P.R. 1982. Containerized and nursery production of Paulownia tomentosa. U.S. For. Serv. Tree Plant. Notes 33 (1): 29-33.

Paulownia tomentosa seedlings were grown in containers in a greenhouse for 110 days and a nurserybed for 193 days. Paulownia growth was slow during the first several weeks of growth in both situations. Later in the season, growth accelerated considerably. Top and root growth was checked when nursery seedlings were root pruned by a tractor-pulled lifting bar, however, roots were more fibrous than non-root-pruned seedlings. Detailed procedures for seedling production are presented.

(author's abstract)

19. Bedker, P.J. and R.A. Blanchette. 1983. Development of cankers caused by Nectria cinnabarina on honey locusts after root pruning. Plant Dis. 67: 1010-1013.

Nectria cinnabarina can cause damaging cankers on honey locusts (Gleditsia triacanthos var. inermis Willd.), especially on newly transplanted trees. Root pruning was used to simulate transplanting stress on honey locusts. Two days after inoculation, trees (5-8 cm dbh) were root pruned with a mechanical trencher. A trench, 90 cm deep and 15 cm wide, was made 60 cm from the base of the tree on all four sides. Trees that were root-pruned had significantly lower ($P<0.05$) water potentials than unpruned trees. Cankers caused by N. cinnabarina after inoculation to twigs, branches, and stems were larger on trees that were root-pruned than on unpruned trees. Uninoculated wounds closed more slowly on trees that were root-pruned than those that were not root-pruned.

(edited author abstract)

20. Benson, A.D. 1974. Some effects of nursery practice on Pinus radiata D. Don seedlings and early plantation establishment. M.Sc. thesis for Australian National University. 147 p.

The effects of certain nursery practices on 1-0 Pinus radiata D. Don seedlings and early plantation development were investigated in an attempt to determine the factors influencing planting stock quality.

Seedlings were raised in a variety of seedbed density and wrenching intensity treatments under otherwise routine nursery conditions. Planting stock characteristics were determined at two planting dates using common grading criteria. Increasing seedbed density and wrenching frequency both reduced seedling size but the former reduced while the latter increased seedling quality. Moisture content, dry weights and RGR were analyzed to document the seasonal development of the seedlings. Two years after outplanting, tree size and survival were reduced for plants raised at high seedbed densities but were increased by moderate wrenching in the nursery.

(edited author's abstract)

21. Benson, A.D. and K.R. Shepherd. 1977. Effects of nursery practice on Pinus radiata seedling characteristics and field performance: II. Nursery root wrenching. N.Z. J. For. Sci. 7: 68-76.

Seedlings were raised under routine nursery conditions and subjected to a variety of root wrenching and fertilizer treatments. Planting stock characteristics were determined at time of lifting using routine grading criteria. Increased wrenching frequency reduced

seedling size, shoot moisture content and foliage concentrations of nitrogen and phosphorus but improved other aspects of seedling quality.

Field performance of planting stock was determined for two planting dates on a moderately severe site prepared for routine plantation establishment. Tree survival, size and form were improved by moderate wrenching treatments and these improvements were still evident in the fifth year after planting.

Mid-autumn planting produced the most distinct differences between unwrenched and wrenched stock. Differences were less marked for mid-winter plantings but wrenching still reduced the incidence of leader damage from 70% to 5%. Unwrenched stock displayed a high incidence of multileaders at two years as a result of initial leader deaths but rarely did this malformation persist at five years after planting.

(authors' abstract)

22. Blake, T.J. 1983. Transplanting shock in white spruce: effect of cold storage and root pruning on water relations and stomatal conditioning. Physiol. Plant. 57: 210-216.

White spruce (Piceae glauca (Moench) Voss seedlings were preconditioned by cold storage and root pruning and a study was made of the effects of conditioning on root regeneration and stomatal adaptation following transplanting.

Root pruning (0 to 75% of the initial root area) of dormant seedlings immediately prior to transplanting did not confer any detectable physiological advantage in either cold-stored or freshly-lifted seedlings. Transpiration rates and stomatal resistance were not greatly affected by root pruning in the 6 week period after planting and root pruning did not greatly alter the response to drought.

Cold-stored seedlings appear better able to avoid transplanting shock and an early drought despite delayed root growth as evidenced by a/ a delay in flushing of new shoot growth and b/ pre-conditioning of the stomatal apparatus which reduced water loss after planting and when moisture was limiting. Seedlings freshly-lifted in the spring did not show these adaptive responses and their stomata were poorly adapted to reduce water loss in the post-planting period after a drought.

(author's abstract)

23. Boyer, J.N. and D.B. South. 1984. Forest nursery practices in the south. South. J. Appl. For. 8: 67-75.

In 1981, a questionnaire was sent to sixty-three forest nurseries in the thirteen southern states to document the practices currently employed to produce southern pine seedlings. The changes in nursery practice over the past fifty years include changes in species favoured, increased mechanical harvesting and increased chemical pest control. In 1980, root-pruning was practiced operationally at several nurseries throughout the south.

24. Brunsden, G.J. 1980. Growth responses and stability of radiata pine chemical weed control and ripping in pumice pasture land. p. 181-185 In Proc. 33rd N.Z. Weed and Pest Control Conf.

A research trial was established on farmland near Rotorua to investigate the growth response and pattern of root development of

radiata pine (Pinus radiata) seedlings to various chemical and mechanical site preparation regimes. After 3 years, trees that had only chemical weed control showed the best overall responses. Mechanical site preparation by ripping, with or without weedicide, resulted in poorer growth and is not recommended for this type of pasture-land soil. Wrenched 1.5/0 seedlings significantly outgrew both wrenched and box pruned 1/0 seedlings. Successful establishment on pumice pasture-land sites depends on the use of high quality tree stocks properly planted and kept weed-free for several months.
(author's abstract)

25. Brunsden, G.J. 1981. Box pruning trials and field results. p. 142-153 In Forest nursery and establishment practice in New Zealand. N.Z. For. Serv., For. Res. Inst. FRI Symp. No. 22. Part 1.

One of the main objectives of the research into box pruning was to determine whether seedlings prepared by the technique of four-sided lateral pruning and undercutting, performed as well as seedlings treated by conventional ways. These trials have proved that they do, and comparable performance may be anticipated from seedlings of both treatments on any site.

Planting stock, prepared by box pruning characteristically has a root system of sound architectural form that may be packed, transported and most importantly planted with the minimum of damage and distortion.

Mechanized cross cutting of beds will not be operational until suitable equipment and beds are developed. Box pruning remains to be an elite conditioning regime.

26. Bunting, W.R. and G.R. McLeod. 1984a. Conditioning red pine: Influence on performance after overwinter frozen storage. Ont. Min. Natur. Resour. Nursery Note 99. 10 p.

Experience at Orono with overwintered frozen stored 3+0 red pine (Pinus resinosa Ait.) stock has shown reduced survival and growth after spring outplanting. In 1980, four treatments of root pruning and wrenching were tried in an attempt to increase the survival and growth of 3+0 red pine. All four treatments included a mid April, 10 to 15 cm pruning and then combinations of a second pruning and varying wrenching regimes. During three years of measuring, root pruning and the frequency of root wrenching were found to have a beneficial effect on the survival of overwinter frozen stored red pine. The effectiveness of the treatments may have been reduced by the depth of the pruning since there was no equipment available to prune shallowly.

27. Bunting, W.R. and G.R. McLeod. 1984b. The effect of root pruning and wrenching on 2+0 and 3+0 red pine seedlings. Ont. Min. Natur. Resour. Nursery Note 100. 11 p.

Red pine (Pinus resinosa Ait.) root pruned in July of the 2+0 year and root wrenched every three weeks until October showed a significant gain in the Root Area Index over normally treated stock in both the 2+0 and 3+0 years. It also showed significantly better survival after outplanting during a season when serious drought conditions prevailed for a large part of July, August and September. The four treatments carried out in 1981 consisted of root pruning at

10 to 15 cm and root pruning at 5 to 8 cm combined with wrenching at three week intervals, six week intervals or no wrenching at all.
(edited authors' abstract)

28. Bunting, W.R. and G.R. McLeod. 1984c. More root pruning and root pruning and wrenching of rising 3+0 red pine. Ont. Min. Natur. Resour. Nursery Note 103. 5 p.

A trial was carried out to determine if shallow root pruning or shallow root pruning plus wrenching would reduce the size of 3+0 red pine (Pinus resinosa Ait.) stock for outplanting and reduce or eliminate the species inability to initiate root growth soon after outplanting. The four treatments consisted of a control (no pruning or wrenching) a single pruning and wrenching, and a single pruning and then wrenching at either three week or six week intervals all done at a depth of 7.5 to 10 cm. Root pruning followed by wrenching reduced the height, dry weight and diameter of the seedlings and reduced the T/R ratio, producing a better looking seedling for planting. Survival after outplanting in a year with adequate soil moisture was not affected by treatment. Current height in the first year after planting was reduced in the most severely wrenched treatments but these differences had disappeared by the end of the second season.

29. Burdett, A.N. and D.G. Simpson. 1984. Lifting, grading, packaging and storing. p. 227-234. In M.L. Duryea and T.D. Landis (eds.) Forest nursery manual: production of bareroot seedlings. Martinus Nijhoff/Dr. W. Junk, the Hague.

While being lifted, tree seedlings are subject to mechanical damage. At the same time, their foliage may be inoculated with soil-borne spores of storage-mold fungi. During subsequent handling and storage, stock condition may change rapidly as a result of desiccation, molding, metabolic activity, or developmental processes. Damage to or deterioration of stock during and after harvest may be minimized through: choice of the method and date of lifting; prelift root pruning, fungicide application, and physiological condition; and post-lift control of stock water potential and temperature. Grading can improve stock quality either by identifying inferior seedlings or batches of stock for culling or by revealing deficiencies in quality that can be avoided in the future through changes in stock-production techniques. To be useful, grading must be in accordance with standards which reflect the stock characteristics necessary for satisfactory field performance. To improve stock quality through changes in cultural and handling practices, nursery managers must investigate the effects of alternative practices on the field-performance potential of the stock they produce.

Root pruning of field-grown seedlings contributes to a compact root system which is beneficial in proper planting.
(edited authors' abstract)

30. Burgar, R.J. 1965. Horizontal and vertical root pruning of 1-0 jack pine. Ont. Dept. Lands For. Nursery Note 9. 6 p.

In 1963, at the Thunder Bay nursery, a test was established to determine the top/root ratios of root pruned jack pine (Pinus banksiana Lamb.) at the end of the 2-0 year and the field survival

and growth of the treated stock. Four treatments; root pruned horizontally at a four inch depth, pruned vertically, pruned horizontally and vertically and a control of no pruning were performed before growth started in the 2-0 year. No wrenching was done. Results show that the root pruning treatments alone used were not reliable methods of improving top/root ratio of 2-0 jack pine at that nursery and there was no significant effect on the first year's field survival and growth.

31. Cameron, R.J. 1969a. The effect of wrenching on root systems of P. radiata seedlings. p. 117-119 In Forest nursery and establishment practice in New Zealand. N.Z. For. Serv., For. Res. Inst. FRI Symp. No. 9.

    During 1966 and 1967 measurements were made of the differences between wrenched and unwrenched seedlings with particular attention to the root systems. Wrenching reduced the growth of both root systems and shoots. Repetitive wrenching has a greater effect on root weight than single wrenching. Wrenched seedlings had a larger surface area than unwrenched seedlings.

32. Cameron, R.J. 1969b. The use of transpiration suppressants. p. 121-122. In Forest nursery and establishment practice in New Zealand. N. Z. For. Serv., For. Res. Inst. FRI Symp. No. 9.

    Tree seedlings are liable to suffer from desiccation during wrenching, at lining out, in transport, while in storage or immediately after being planted. FRI experiments, investigating the use of various compounds to reduce water loss through transpiration, include compounds forming surface films, monomolecular surface films and metabolic inhibitors. The success of the treatments were variable. Further investigations were planned.

33. Cameron, R.J. and D.A. Rook. 1969. Wrenching as a means of conditioning planting stock. p. 111-117. In Forest nursery and establishment practice in New Zealand. N.Z. For. Serv., For. Res. Inst. FRI Symp. No. 9.

    Key aspects of existing knowledge of root pruning and wrenching are reviewed with special emphasis on the physiological basis for the technique. Problem areas and future research needs were identified.

34. Carlson, W.C. and M.M. Larson. 1977. Changes in auxin and cytokinin activity in roots of red oak (Quercus rubra) seedlings during lateral root formation. Physiol. Plant 41: 162-166.

    Quercus rubra L. seedlings were partially root pruned to induce formation of new laterals. Auxins in root extract fractions that cochromatographed with IAA, and cytokinins in root xylem sap fractions that cochromatographed with zeatin and zeatin riboside, were quantified by bioassays at 24 h intervals after pruning. Auxin activity sharply increased in the first 24 h and then decreased to prepruning levels. Cytokinin activity also increased during the first 24 h. New laterals appeared 4 to 5 days after pruning. The possible sources and role of these two hormones in root initiation are discussed.

    (authors' abstract)

35. Chavasse, C.G.R. 1973. Mechanization of nursery production, forest establishment and tending in New Zealand. p. 17-19, 38-39. N.Z. For. Serv., For. Res. Inst. FRI Symp. No. 13. Vol. 2.

Specifications for and use of wrenchers, undercutters and pruners are outlined. A system of rating the equipment has been compiled by users of the machinery and a synopsis of specific uses is presented.

36. Chavasse, C.G.R. 1978a. Comments on effects of wrenching on drought avoidance of Douglas fir seedlings. U.S. For. Serv. Tree Plant. Notes 29 (3): 17, 35.

Seedling cull rates can be reduced and seedling field performance can be improved by creating even spacing among individual seedlings. Root damage during lifting is minimized by pruning and wrenching. Alternate conditioning regimes include: a deepish undercut, lateral root pruning on four sides carried out twice, and a shallower undercut with no wrenching.

37. Chavasse, C.G.R. 1978b. The root form and stability of planted trees with special reference to nursery and establishment practice. p. 54-64. In E. van Eerden and J.M. Kinghorn (Eds.). Proceedings of the root form of planted trees symposium. Victoria, British Columbia, May 16-19, 1978. B.C. For. Serv./Can. For. Serv. Jt. Rep. No. 8.

Instability in stands is related to the method of preparing planting stock in the nursery, to methods of cultivating planting sites, to planting methods, and to silviculture, including thinning and rotation length, all of which the forest manager is able to manipulate.

The objective of planting should be to use methods which allow the root system to develop a form as close as possible to that of naturally regenerated trees.

Conventional ways of raising seedlings in nurseries (whether bare-rooted or container-grown) make it difficult to distribute roots satisfactorily during normal planting operations, whether by machine or with hand tools. A method of conditioning trees is described which includes undercutting and four-sided root pruning, and which promises to alleviate this problem.

On all sites any form of soil compaction inhibits taproot growth. Overall cultivation with discs or rotary hoes tends to induce or aggravate toppling, and it is suggested that a better method is to prepare compacted sites with winged rippers (to give maximum soil shatter).

(edited author's abstract)

38. Chavasse, C.G.R. and G.C. Weston. Eds. 1969. Wrenching. In Forest nursery and establishment practice in New Zealand. N.Z. For. Serv. FRI Symp. 9: 108-136.

Description of wrenching in New Zealand including wrenching technique, timing and effects on tree physiology. Some variations in nursery practice are presented in the form of a response to a questionnaire.

39. Cleary, B.D., R.D. Greaves and P.W. Owston. 1978. Seedlings. p. 63-97. In B.D. Cleary, R.D. Greaves and R.K. Herman, Regenerating Oregon's Forests. Oreg. State Univ. Ext. Serv., Corvallis, Oregon.

All aspects of seedling culture including conditions affecting growth and dormancy, physiology, morphology, types of stock and seedling handling are discussed. Undercutting and wrenching affects depend on how and when these procedures are done. A review of findings from published literature is presented with a discussion of methods and results.

40. Clifford, E.D. 1956. Seedbed root pruner. U.S. For. Serv. Tree Plant. Notes 24: 11-12.

Examination of seedlings at the Chittenden nursery after horizontal root pruning at five to six inches showed that only 20% of the roots were vertical and therefore had been pruned. The need to side prune led to the development of a rolling coulter type pruner. Approximately 50% of the main horizontal roots were pruned when the side pruner was tested in the spring of 1955. Lifting was facilitated by vertical pruning.

41. Coker, A. 1984. Nitrogen status of Pinus radiata seedlings after undercutting: Changes in total, soluble and insoluble nitrogen. N.Z. J. For. Sci. 14: 277-288.

Changes in total, soluble, and insoluble nitrogen and chlorophyll concentrations in Pinus radiata D. Don seedlings were monitored for 56 days after a single undercutting (root pruning). After undercutting there was a marked reduction in total soluble and insoluble shoot nitrogen concentration. Some of this mobilized nitrogen contributed towards lateral root growth while 15% was lost, possibly from the damaged root as exudate. Twenty-one days after undercutting, total seedling nitrogen content began to improve, coinciding with lateral root dry matter gains. By 56 days, undercut seedling nitrogen content approached that at Day 0, while control seedlings had acquired an additional 20.6 mg nitrogen.

Lateral root dry weights and nitrogen content of undercut seedlings were higher than those of control plants after 56 days. However, soluble nitrogen concentration in lateral roots of undercut seedlings was not significantly different from the controls, although total and insoluble nitrogen concentrations were significantly below control plant values.

There was no significant difference in chlorophyll concentration of needles between control and undercut seedlings.

(author's abstract)

42. Darby, S.P. Jr. 1962. Intensified nursery practices - the key to high quality, custom-grown field-graded forest tree seedlings. U.S. For. Serv. Tree Plant. Notes 52: 7-11.

Custom-grown, field-graded seedlings have less root exposure during packaging and save both time and money. The techniques for accomplishing this are exacting and involve drainage, nutrient levels, uniform distribution of fertilizer, good seed, seed bed density and mulching. Root pruning when combined with other treatments results in a better balanced plant. Custom-grown, field-graded seedlings can be supplied to landowners in a more vigorous condition at a lower cost than nursery graded stock.

43. Davey, C.B. 1964. Root pruning in forest nursery management. p. 38-42 In Proc. Region 8 Forest Nurserymen's Conference, Aug. 19-20, 1964. Morganton, N.C.

The purposes of root pruning are to increase uniformity of stock, ease of planting and initial field survival. Root pruning also stimulates lateral root development and allows production of seedlings rather than transplants. The hazards of root pruning include reduced field survival if improperly done, additional expense and increased risk of root disease. General conclusions regarding the value of root pruning in forest nursery management were reached through a review of the literature.

44. Davey, C.B. 1984. Pine nursery establishment and operations in the American tropics. p. 18-19. N.C. State Univ., CAMCORE Bull. on Trop. For. No. 1. 36 p.

In the American tropics, root pruning and wrenching are used in nursery operations to promote lateral root development. Root pruning is done at a depth of 15 cm when seedlings reach a height of 15 cm. The final undercutting occurs one month before lifting. Lateral root pruning with rolling coulters is scheduled two or three days before lifting. Root pruning of any kind is followed by a cycle of irrigation.

45. Dierauf, T.A. and H.L. Olinger. 1982. A study of undercutting, lateral root pruning and top clipping in loblolly pine nursery beds. Virginia Div. For., Dep. Conserv. Econ. Dev., Occas. Rep. 58. 6 p.

Loblolly pine (Pinus taeda) seedlings were undercut and lateral root-pruned in the nursery seedbeds on three different dates: August 8, September 1 and October 4. Half of each plot was top-clipped on September 1.

In the seedbeds, diameter was reduced by undercutting, but not by lateral-root pruning or top-clipping. Top length was reduced by undercutting and top clipping, but not by lateral pruning. Only the August undercutting had a noticeable effect on root system morphology.

After planting in the field, none of the treatments affected survival, but undercut seedlings grew slightly better.

(authors' abstract)

46. Duryea, M.L. 1981. Water relations, growth and survival of root-wrenched Douglas fir seedlings. Ph.D. thesis for Oregon State Univ. 40 p.

Root wrenching of seedlings (severing the roots 15 cm below the soil surface) was investigated in the first study as a nursery practice to improve growth and survival of field-planted Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) from six local seed sources in the Pacific Northwest. At lifting, shoots of wrenched seedlings were shorter, lighter and had smaller diameters than those of unwrenched seedlings. Among seedlings from four of the seed sources, wrenching resulted in significantly lighter taproots but did not significantly affect lateral root and total root weights. There were no significant differences between these measurements among wrenched and unwrenched seedlings from the other two sources. Mainly because of lighter shoots, shoot-root ratios were smaller for wrenched than for unwrenched seedlings. In no case did root wrenching improve field

height growth or survival after one year, and among four of the sources shoot growth was significantly less than that of unwrenched seedlings.

In the second study, root wrenching was investigated as a nursery practice to precondition Douglas fir seedlings to droughty field conditions. Wrenching shocked the seedlings while in the nursery, lowering plant water potential and transpiration rate. After planting, however, wrenched and unwrenched seedlings transpired at equal rates when exposed to stress with osmotic solutions of Polyethylene Glycol 1000 and under field conditions. Throughout exposure in pots to a drought simulating the Pacific Northwest summer drought, wrenched and unwrenched seedlings did not differ in plant water potential, leaf relative water content or seedling condition. However, all wrenched seedlings of four seed sources reflushed in the middle of the drought and had significantly fewer active roots than unwrenched seedlings. Among the four seed sources used, differences in ability to withstand drought were apparent.

(author's abstract)

47. Duryea, M.L. 1984. Nursery cultural practices: Impacts on seedling quality. p. 143-164 In M.L. Duryea and T.D. Landis (eds.). Forest nursery manual: Production of bareroot seedlings. Martinus Nijhoff/Dr. W. Junk, The Hague.

Better understanding and implementation of nursery cultural practices to improve seedling quality will enable better matching of seedlings to forest sites, reducing the chance of regeneration delay and improving future growth of forest stands. This chapter reviews a number of important cultural practices and the ways in which they affect indicators of seedling quality (morphology and physiology) and ultimately, field performance (growth and survival). Early spring sowing produces larger seedlings that can complete their growth and be hardened by midsummer. Lowering seedbed density results in more seedlings from a given amount of seed and can improve field survival and growth. A nursery irrigation schedule that imposes moderate stress on seedlings in midsummer induces earlier budset and seedling dormancy and increases field-survival potential. Most often, field survival and growth are improved with growing-season fertilization in the nursery; fall fertilization also may increase field growth of Northwest species. Root wrenching in dry soil and (or) hot, dry weather without immediate irrigation can greatly stress Douglas fir seedlings and should be avoided because of increased chance of seedling mortality in nursery beds or reduced growth later in the field. Wrenching to mildly stress seedlings can induce budset and hardening and may benefit field growth and survival. Top pruning, to control shoot height and achieve crop-size uniformity, should be done during the period of active seedling growth in early summer to ensure proper development of terminal buds. Transplant seedlings have more fibrous root systems, larger stem diameters, and lower shoot:root ratios than seedlings of comparable age grown at a standard density; seedlings are most commonly transplanted in spring and are outplanted as 1+1s or 2+1s. It is important for nursery managers to be aware of interactions among the various nursery practices they employ; if a current practice is altered or discontinued or a new practice added, careful attention should be given to the effect of this change on other cultural practices in the nursery.

(author's abstract)

48. Duryea, M.L. and D.P. Lavender. 1982. Water relations, growth and survival of root-wrenched Douglas fir seedlings. Can. J. For. Res. 12: 545-555.

Root wrenching in the nursery was investigated in relation to Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) seedling growth and survival under field conditions. Immediately after wrenching, seedlings had lower plant water potential and leaf conductance of water vapor than unwrenched seedlings. At lifting, shoots of wrenched seedlings were shorter, lighter, and of smaller diameter than those of unwrenched seedlings. Seedlings from four of six seed sources tested had significantly lighter taproots after wrenching, but lateral root and total root weights were not significantly different. Mainly because of lighter shoots, wrenched seedlings had smaller shoot-root ratios than controls. After field planting, wrenched and unwrenched seedlings at a droughty site did not differ in leaf conductance or plant water potential, and throughout exposure to a simulated summer drought in pots, all seedlings showed equal plant water potential, leaf relative water content, and seedling condition. However, wrenched seedlings of four seed sources did not set a bud as quickly during drought and had significantly fewer active roots than unwrenched seedlings. In no case did root wrenching improve growth or survival in the field, and among four seed sources shoot growth was significantly less than that of unwrenched seedlings after 3 years.

(authors' abstract)

49. Dusek, V. 1967. Application of the root-undercutting method in tending transplants. Commun. Inst. For. Cech. 5: 123-140.

Undercutting was investigated as a method for improving planting stock including transplants. The experiments, started in 1958, were aimed at evaluating the influence of undercutting on the formation and development of root systems and at finding the most suitable time and depth for the roots to be undercut. The results of these experiments provided basic specifications for undercutting, including information on age, growth stage, season and depth of undercutting for twenty tree species.

Undercutting can be used for outplanted seedlings which have not been transplanted, for holding seedlings and transplants for another year in nursery beds and for 4- to 6-year-old stock which have been transplanted.

50. Dykstra, G.F. 1974. Undercutting depth may affect root regeneration of lodgepole pine seedlings. U.S. For. Serv. Tree Plant. Notes 25 (1): 21-22.

Basal sweep and toppling in lodgepole pine (Pinus contorta Dougl.) may be caused by lack of development and growth of a dominant tap root after the primary tap root has been severed by root pruning, undercutting or lifting. In the study, seedlings were undercut six weeks after germination at depths of three, six and twelve inches and then allowed to grow for two months. There were no significant differences in total root weight, shoot weight or shoot-root ratio among different undercutting depths but seedlings pruned at a three inch depth grew most in tap root length and dry root weight.

51. Edgren, J.W. 1975. Wrenching - recent developments in an old technique. p. 50-59 In Proceedings of Western Forest Nursery Council Meeting, Portland, Oregon. Aug. 5-7, 1974.

In-depth work on wrenching has been published by scientists at the Forest Research Institute, Rotorua, New Zealand and these results are summarized with respect to methods and benefits. Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) and ponderosa pine (Pinus ponderosa Laws.) seedlings were undercut and wrenched in a limited trial. The ponderosa pine control plots were undercut at a 10 to 15 cm depth in early May and the treatment plots were undercut July 1 at a depth of 10 to 15 cm and wrenched at a depth of 15 to 20 cm three times at three week intervals. Control plots containing Douglas fir were undercut near June 1 while treatment plots were wrenched twice. The results of wrenching Douglas fir seedlings were inconclusive because of treatment irregularities. Wrenched ponderosa pines developed best and had a greater top-root ratio. This study raised more questions than it answered.

52. Edgren, J.W. 1981. Field performance of undercut coastal and rocky mountain Douglas fir 2+0 seedlings. U.S. For. Serv. Tree Plant. Notes 32 (3): 33-36.

The effects of a single undercutting in the spring on the field survival and growth of coastal and rocky mountain varieties of Douglas fir (Pseudotsuga menziesii). The treatment consisted of undercutting both varieties of 1+0 stock at a depth of 15 cm and a control of both varieties of seedlings which were not undercut. Undercutting significantly improved the survival of outplanted coastal seedlings but did not improve the growth of either variety after outplanting. Field performance of the rocky mountain variety was not improved in any way. Different cutting dates and depths should be tested for different varieties of Douglas fir, particularly deeper undercutting of rocky mountain seedlings. The practice of wrenching should also be examined.

53. Edgren, J.W., M. Greenup and J.M. Reynolds. 1978. An operational root wrenching trial at Humboldt nursery. p. B69-B76 In Conference and workshop proceedings of the Western Forest Nursery Council and Intermountain Nurserymen's Association, Aug. 7-11, 1978. Eureka, California.

Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) 2+0 seedlings were undercut July 17 and wrenched September 2, 22 and October 13. Control seedlings were neither undercut nor wrenched. Stem diameters, top heights, and top and root oven dry weights were recorded. The conclusions reached were that the timing of the treatments adversely affected desirable seedling characteristics. Undercutting occurred while diameter growth was beginning and wrenching occurred during maximum root growth so the result was stunted growth.

It is recommended that two undercutting-wrenching schedules be tested. To curtail height growth and promote caliper and root growth, begin the root treatment by undercutting before top growth starts. To permit height growth and produce a less favourable top-root balance, undercut after top growth has taken place. These schedules appear superior to schedules which recommend treatment when seedlings reach a specific height because the desired height system ignores the natural growth rhythms of the seedlings.

54. Eide, R. and J. Grimm. 1958. Oblique root pruning blade. U.S. For. Serv. Tree Plant. Notes 31: 6-7.

An oblique root pruning blade was designed to eliminate the bunching up or folding over of rootlets on the perpendicular root pruning blade and the time consuming task of cleaning the blade. To keep the blade horizontal, stabilizing fins need to be attached to each side of the blade carrier. Root pruning should be done just before rain to minimize loss of seedlings, otherwise post-pruning irrigation is recommended.

55. Eis, S. 1968. Lateral root pruning - a promising forest nursery practice. For. Chron. 44: 12-13.

The effects of various root pruning techniques and timing on root regeneration and growth of 1-0 Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) were investigated. The study was carried out in 1967 at the British Columbia Forest Service nursery. Root pruning at a depth of six inches did not decrease the height increment of seedlings. For the best development of dense and compact root systems, the bottom pruning should be done early in spring and the side pruning, on both sides of the row simultaneously, around the middle of June.

56. Eis, S. and J.R. Long. 1972. Lateral root pruning of Sitka spruce and western hemlock seedlings. Can. J. For. Res. 2: 223-227.

This study was designed to find a satisfactory method and time for root pruning western hemlock (Tsuga heterophylla (Raf.) Sarg.) and Sitka spruce (Picea sitchensis (Bong.) Carr.) seedlings, to produce dense and compact root systems on 2+0 stock without transplanting. All root pruning was done by sidecutting with a sharp spade 5 cm or 9 cm from the row, one side at a time or sides of the row simultaneously. Specifically studied were the effect of root pruning on height growth of seedlings, the regeneration and growth of root systems following monthly pruning from May until September.

Root pruning did not significantly affect the height growth of seedlings, regardless of the month the treatment was carried out. The densest root systems were produced by pruning before the end of June and by pruning both sides of the rows simultaneously. Because of the lack of lateral root development early in the second growing season, the best time to prune seedlings equidistant between the rows (9 cm) appears to be early in July for hemlock and in mid-July for spruce. If early pruning is carried out on 2+0 seedlings, it should be 6 cm from the row. The results of this study are not necessarily applicable to other species or environmental conditions.

57. Eis, S. and J.R. Long. 1973. Root pruning in the nursery. U.S. For. Serv. Tree Plant. Notes 24 (1): 20-22.

Douglas fir (Pseudotsuga menziesii (Mirb.) Franco), Sitka spruce (Picea sitchensis (Bong.) Carr) and western hemlock (Tsuga heterophylla (Raf.) Sarg.) seedlings, drill sown in rows 18 cm apart, were horizontally and laterally pruned at different times during their second growing season in two root pruning studies. They were also pruned at different distances from the row. The results suggest that horizontal pruning of all three species be done as early in the year as soil conditions permit. In lateral pruning the best dates

for good root regeneration appear to be June 20th for Douglas fir, the beginning of July for spruce and the middle of July for hemlock. If top growth has been adequate, Douglas fir should be horizontally pruned again at the beginning of August to encourage formation of terminal buds and hardening of stock.

58. Escobar, R.R., B.M. Espinosa and V.G. Medina. 1977a. Efectos de poda y descalce de raices en el desarrollo de pino insigne (Pinus radiata D. Don). Boletin de Investigacion, Centro de Ciencias Forestales, Universidad de Concepcion. No. CCF-1. 20 p.

Several undercutting and wrenching regimes were tested on 1-0 Monterey pine (Pinus radiata D. Don) seedlings. The treatments consisted of a control, undercutting after reaching a height of 15 cm, and undercutting followed by wrenching seven, fourteen, twenty-one and twenty-eight days after.

Treated seedlings had shoot length reductions of 27 to 35% when compared to the control seedlings. Any treatment resulted in better root/shoot ratio than control seedlings. The best results were achieved by undercutting and wrenching seven days later.

(edited authors' abstract)

59. Escobar, R.R., B.M. Espinosa and V.G. Medina. 1977b. Efectos de poda y descalce de raices en la sobreviuencia y desarrollo inicial de pino insigne (Pinus radiata D. Don). Boletin de Investigacion, Centro de Ciencias Forestales, Universidad de Concepcion. No. CCF-2. 21 p.

First year survival and third year growth of Monterey pine (Pinus radiata D. Don) seedlings were analyzed after outplanting on a sandy soil plantation. The treatments which were applied to 1-0 stock were no conditioning, undercutting once and undercutting and wrenching either seven, fourteen, twenty-one or twenty-eight days later. 1-1 transplants were also used in the study.

Seedlings which were undercut and wrenched 14 days later had the best results. Seedling survival was 14.8% and height increment was 21.8% better than unconditioned seedlings.

(edited authors' abstract)

60. Faulkner, R. 1953. Early observations on the root development of one-year-old Corsican pine seedlings following root pruning. Scott. For. 7 (1): 23-26.

At the Newton Forestry Commission nursery, three beds of Corsican pine (Pinus laricio var. corsicana Loud.) 1+0 seedlings were root pruned in the early spring of 1952. The object of the pruning was to test the efficiency of a sledge type of root pruner and secondly, to observe the effect of root pruning on subsequent growth and survival of the plants. In February, one bed of seedlings was undercut at a depth of 3-1/2 inches and in March, two more beds were undercut, one at a depth of 4-1/2 inches and the other at a depth of 5-1/2 inches.

Root pruning, at all depths tested, promoted early vigorous root development of secondary and tertiary roots. Root pruning at the 3-1/2 inch depth in February reduced the growth of the shoot leader but root pruning at a depth of 4-1/2 and 5-1/2 inches produced no adverse effects on the growth of the shoot leader.

61. Feret, P.P. and R.E. Kreh. 1986. Effect of undercutting on loblolly pine seedling size and its relation to root growth potential. South. J. Appl. For. 10: 24-27.

Loblolly pine (Pinus taeda L.) seedlings undercut using five different treatments extending from July to September exhibited significant alteration of shoot and root biomass. Root growth potential (RGP) (measured by number of new elongating roots) was not significantly altered by undercutting. Undercutting did significantly alter the RGP/root weight ratio and the RGP/shoot weight ratio because of both concomitant changes in root and shoot biomass and changes in seedling physiology.

Root growth potential and efficiency of existing old roots to produce new roots were not well correlated with seedling size.

(authors' abstract)

62. Foster, C.H. 1932. Improvements in planting stock production. J. For. 30: 797-799.

Two-year-old seedlings had poor survival when planted on land with heavy soil and rank ground cover, which led to an increased demand for transplants. The production of transplants necessitated more land and increased costs which led to a sacrifice of quality for quantity. Around 1927, it was recognized that improvement in forest planting stock had to be made. These included reducing the density of seedbeds and inoculating nursery soil with mycorrhiza. Several nurseries started epxerimenting with the three-year root-pruned seedling. The advantages to pruning instead of transplanting were lower production costs and planting stock which had normal lateral roots.

63. Fraser, D.A. 1976. Management of tree growth and research plantations. p. 192-201 In Proceedings of the 12th Lake States Forest Tree Improvement Conference. August 1975. U.S. For. Serv., Gen. Tech. Rep. No. NC-26.

Changes in vegetative growth and reproductive responses in white spruce (Picea glauca (Moench) Voss) and black spruce (Picea mariana (Mill.) B.S.P.) resulting from control of soil moisture, by means of overhead sprinklers, extension of the photoperiod by means of incandescent lamps and raised thermoperiod by means of heated plastic shelters are reported. When the saplings were 7 and 8 years old, they were root pruned twice in a circle 18 inches from the trunk at a depth of 8 inches. Root pruning had an immediate stimulatory effect but subsequently reduced vigor had deletorious effects on conelet production.

64. Ghosh, R.C., R.P. Singh and K.K. Sharma. 1974. Standardization of nursery technique of tropical pines. III. Root pruning of Pinus patula, Schiede and Deppe, seedlings in nursery - a study. Indian For. 100: 544-547.

Pinus patula (Schiede and Deppe) seedlings were studied to determine the desirability of pruning at the time of pricking out. The three treatments consisted of a control, knotting the roots 3.5 cm below the collar, and pruning the roots to a length of 3.5 cm. Measurements were made on the survival percentage, number of root tips, root and shoot length, crown width and dry weight of root and

shoot. In all the determinates measured, root pruned seedlings were superior although in some cases the difference was not large enough to be statistically significant. Root pruning at the time of pricking out Pinus patula seedlings is recommended.

65. Gingerich, R.E. and H.G. Hertel. 1962. The effect of horizontal and vertical root pruning on 2-0 Austrian pine (Pinus nigra Arnold). U.S. For. Serv. Tree Plant. Notes 52: 1-6.

Two-year-old Austrian pine (Pinus nigra Arnold) seedlings were studied to determine if root pruning in place would produce seedlings comparable to transplants at a comparative cost. The three treatments included a control which was allowed to develop to normal 3-0 stock, horizontal and vertical root pruning and transplanting. Horizontal pruning was done with a lifting bar and vertical pruning with a rolling coulter root pruner. On the basis of top weight, total weight, root weight and root/top ratio, transplants and root pruned seedlings did not vary significantly from each other and both were more vigorous and exhibited greater top-root balance than the controls. With no major physical differences between transplants and root pruned seedlings, the choice for planting should be based on production costs and space requirements. Possible refinements for commercial production of root pruned seedlings include reducing seedbed density, pruning between first and second growing season and before bud break, and the use of a knife-type lateral root pruner to give a sharper cut and less root injury.

66. Gleed, J.A. 1967. Mechanization in a forest nursery. N.Z. J. For. 12: 174-182.

The mechanical aspects of raising 1/0 Pinus radiata at the Tasman Pulp and Paper Company's tree nursery at Te Teko are described. The special needs of a large-scale planting programme have provided the opportunity to establish "production-line" techniques in a nursery, with an improvement in tree quality and a reduction in unit costs.

Pruning and wrenching improve tree quality and are mechanized to improve efficiency. The first root pruning is done with a piano wire strained between two vertical blades attached to either side of the blade. The blades are mounted on a tool bar attached to a tractor's three-point linkage. The tractor is able to move at speeds up to 5 mph while the wire snaps the roots off. Subsequent wrenchings are normally made with a conventional blade.

Mention is made of the limits of the existing methods and equipment, and how the problems of an annual production in excess of seven million 1/0 P. radiata seedlings may be handled.

(edited author's abstract)

67. Göbl, F. 1966. Beobachtungen über einen Wurzelschnitt bei Zirbenjungpflanzen. Centralbl. Gesamte Forstwes 83: 104-108.

The influence of root cutting on the development of mycorrhizae was studied on 5 year old Swiss stone pines (Pinus cembra). Compared with the untreated control, the treated plants showed better developed mycorrhizae, while the total root length and the length of the compact root system was smaller. Although this is the result of the first investigation on Swiss stone pine, root cutting should generally be favorable for the development of roots and mycorrhizae. The method can be recommended for planting projects.

(author's abstract)

68. Goudie, H.A. 1935. Tree growing in the nursery: The practice and value of wrenching. N.Z. J. For. 3: 212-214.

An insightful commentary on the value of root wrenching in improving stock quality and outplanting performance is presented. The conceptual basis of the technique is described with respect to root severance, soil aeration and the modification of growth processes. The value of wrenching appears to be the increased soil aeration.

69. Gregory, J.D. and C.B. Davey. 1977. Subsoiling to stimulate flowering and cone producton in a loblolly pine seed orchard. South. J. Appl. For. 1 (2): 20-23.

Subsoiling in a loblolly pine seed orchard was studied in relation to female flowering, cone production, root growth and soil bulk density. Subsoiling was conducted in late July 1973 in a nine-year-old seed orchard on sandy soil. The average number of female flowers per tree in 1974 and cones per tree in 1975 was considerably greater in the subsoiled plots than in the control plots. There was large tree-to-tree variability. The 1975 flower crop was not affected by the subsoiling treatments. Root excavations made two years after the subsoiling was done indicated vigorous generation and growth of new roots near the ends of cut roots. Soil bulk density was reduced in the upper soil horizons in and adjacent to the subsoiler slits. The stimulating effects on flowering by subsoiling are thought to result principally from the immediate physiological effects of root pruning. (author's abstract)

70. Hallman, R.G. and J. Lott. 1974. Nursery equipment survey report. p. 125-134 In Proceedings of Western Forest Nursery Council Meeting. August 5-7, 1974, Portland, Oregon.

Previous surveys of nurserymen's equipment needs were limited in scope and outdated, so in 1974, a questionnaire was sent to 132 nurseries in the United States. Types of equipment for all areas of nursery operations are presented and the number of nurseries using specific equipment are indicated. In the root pruning area, more than twice as many respondents bottom prune as side prune. Fixed blades are commonly used to bottom prune and discs to side prune. Several nurserymen stated a need for a side pruner.

71. Harstela, P. and L. Tervo. 1981. Rationalization of the production of bareroot plants in Finland. U.S. For. Serv. Tree Plant. Notes 32 (2): 24-29.

New developments in the mechanization of lifting and root pruning of tree seedlings in Finland are reviewed with emphasis on improved working conditions. If sidecutting is performed before undercutting, the resistance of transplants to freeing from the soil is distinctly reduced which improves working conditions. A "test-bench machine" was constructed for root cutting. A mobile J-knife was used to combine side and undercutting.

72. Harstela, P. and L. Tervo. 1983. Root pruning. p. 19-22 In Technology of the production of bare-root seedlings. Comm. Inst. For. Fenn. 110. 51 p.

The technologies associated with the production of bare-root seedlings and the possibilities of its development in Finland and

some other countries are presented. Technological variables are examined by means of economic, biological labour policy and ergonomical criteria. Root pruning, as a substitute for transplanting, and the lifting of seedlings are analysed more broadly than other aspects of nursery practice and more empirical material has been collected. This is due to greater costs, greater labour requirements, and the ergonomical problems in the production of bare-root plants. Equipment for and techniques of root pruning are reviewed.

73. Hastings, W.G. 1923. Revolutionizing nursery practice. J. For. 21: 180-182.

The production of high class nursery stock in adequate quantities and at prices within the reach of every land owner is the goal of the Vermont State nursery. It was evident that the price per thousand at which nursery stock was sold had a decided effect upon the number of trees planted. To increase planting, nursery stock prices had to be radically lowered. Pruning the roots of seedlings in place and culling out inferior species was a method of nursery practice with some measure of success. The root pruning should be done in the fall and is best accomplished by passing a draw knife 5 or 6 inches beneath the bed. Other methods included a new-style of bed, long and narrow, a seeding drill and a seed bed shade and screen.

74. Hobbs, S.D., S.G. Stafford and R.L. Slagle. 1987. Undercutting conifer seedlings: effect on morphology and field performance on droughty sites. Can. J. For. Res. 17: 40-46.

Bareroot 2-0 Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) and ponderosa pine (Pinus ponderosa Dougl. ex Laws.) seedlings were subjected to five undercutting treatments, which varied by number and depth of undercut and seedling phenology at time of treatment, so that morphological characteristics at lifting and field performance 4 years after planting on droughty south slopes in southwest Oregon could be evaluated. All undercutting treatments significantly reduced seedling top growth, but changes in root system morphology depended upon treatment severity and species. Treatment effects were generally more pronounced in ponderosa pine than Douglas-fir. Multivariate analysis of variance showed significant treatment effects for both species based on seedling morphology at lifting, but discriminant analyses revealed that these differences existed primarily between undercut seedlings, regardless of undercutting treatment, and controls. In Douglas-fir this separation was largely due to differences in seedling height and in ponderosa pine it was due to differences in tap root biomass. However, no treatment effects were detectable 4 years after outplanting for either species despite record high air temperatures during the first growing season, suggesting that morphological differences at lifting were probably not of sufficient magnitude to affect field performance.

(authors' abstract)

75. Huberman, M.A. 1940. Studies in raising southern pine nursery seedlings. J. For. 38: 341-345.

In 1933, an unsatisfactory relationship existed between the number of southern pine seeds planted and the number of plantable seedlings produced. The problem of low germination rates was studied by

experimenting with different treatments including mulching, seed pretreatment (soaking), varying the times of sowing, and irrigation. Parallel laboratory germination tests were made with the same seed lots. The fact that nursery-bed germination was not significantly different from laboratory germination indicated that the problem was in the treatment of the seed in extraction and storage.

The three methods used to increase the percentage of plantable seedlings included root pruning in place, shading and thinning to a given density. Root pruning was done early in June, July and August. Root pruning and shading did not significantly alter the plantable percentage, however, changes in density may significantly affect the number of plantable trees produced.

76. Jakabffy, E. 1969. Rationalizing open ground nurseries: Undercutting and some suitable sowing methods. Sver. Skogsvardsförb. Tidskr. 67: 425-440.

Root pruning is presented as an alternative to transplanting when well-balanced planting stock with a finely divided root system must be produced at low cost.

Pruning may be carried out in two stages: first, on the one side of the root system, after shoot growth has begun; then on the other side, about three weeks later.

Trials with root pruned plants show that they are fully equivalent to tranplants -- 2-R plants compete even with 2+1 transplants.

Economic calculations indicate that quality root pruned plants could be produced on a large scale at least 30 percent more cheaply than comparable transplants. It is conceivable that a considerably greater saving may be attained.

The root pruning technique requires that sowing be sparse and even. A new sowing method for this purpose is presented.

The method is based on the use of prepared seed bands which are considered to have economic, technical and biological advantages over the conventional method and which can also be used for producing transplants.

The costs for production, storage and distribution of seed bands could be recouped through various savings in the later stages of plant production.

(author's abstract)

77. Janouch, K.L. 1927. Effect of spacing and root pruning on the development of transplants. J. For. 25: 62-67.

In 1914, the influence of different spacings in nursery beds on the development of 1-1 and 2-1 jack pine (Pinus divaricata) and western yellow pine (Pinus ponderosa) transplants were tested. Experiments with wide spacing were also used to determine if 1-1 transplants could be made to approach the development of 2-1 transplants. The third trial was to test the effect of root pruning at the beginning of the second year on the development of seedlings in transplant beds. The spacings tried were 1, 1-1/2 and 2 inches within the row and all rows were 6 inches apart. The 1-1/2 x 6 inch spacing produced well balanced trees for both seedling species. Wider spacing resulted in larger trees and higher survival. Even with wide spacing, transplants of the 1-1 class did not develop sufficiently to warrant the use of this class of stock. Root pruning, with a sharp blade at a depth of 9 inches, did not have any beneficial effect.

78. Johansen, R.W. 1955. The effects of certain nursery treatments and site preparations on the vigor and survival of longleaf pine (Pinus palustris Mill.) in the deep sands of the Carolinas. M.S. Thesis for School of Forestry, North Carolina State College. 46 p.

Nursery treatments such as thinning to regulate seedbed density, root pruning to modify the root system and to retard foliage production and fertilizing to increase groundline diameter were investigated to improve the quality of longleaf (Pinus palustris Mill.) seedlings for successful and practical planting on harsh sites. Three site types and preparations were also examined. The seedbed densities tested were 10, 20 and 40 seedlings per square foot. Half of all the seedlings were root pruned once and all seedlings received the same fertilizer treatment except some of the 40 seedlings per square foot density.

Seedlings which were root pruned in mid-season of the first year and grown at a density of 20 seedlings per square foot had better vigor and survival than at the higher density and only slightly less vigor and survival than at the lower density of 10 per square foot. Fertilizer application had a significant effect on seedling vigor and survival.

79. Koon, K.B. and T. O'Dell. 1977. Effects of wrenching on drought avoidance of Douglas fir seedlings. U.S. For. Serv. Tree Plant. Notes 28 (2): 15-16.

Two-year-old (2-0) Douglas fir (Pseudotsuga menziesii) seedlings were wrenched on a monthly or bi-weekly basis at either a 6 inch or 8 inch depth to determine if seedling survival would increase when outplanted on a droughty site. Wrenching was performed during August and September of 1974 and seedlings were outplanted in April 1975. Large root/shoot ratios, low internal water deficits and the percent survival of outplanted seedlings were selected as indicators of drought avoidance. Root/shoot ratios of all wrenched seedlings were significantly greater than unwrenched seedlings. Seedlings undercut at 8 inches showed reduced internal water deficits and improved survival when compared to unwrenched stock. A low nursery bed density was used for the wrenching experiment so the same results may not be obtained from seedlings raised in nursery beds of greater densities.

80. Kummel, J.F., C.A. Rindt and T.T. Munger. 1944. Forest planting in the Douglas fir region. USDA For. Serv., Portland, Oregon p. 59-60.

Root pruning in the beds is done to increase the formation of lateral roots on that portion of the root system that will be lifted with the plant and to retard growth of stock that has to be held in beds a season beyond normal planting age. Root pruning is accomplished by pulling a thin sharp blade through the bed, usually at a depth of 4 to 5 inches. The bed should be irrigated immediately after pruning. Root pruning is not a successful substitute for transplanting and is not much more economical.

81. Laiho, O. 1966. Root-pruning instead of transplantation? Metsätaloudellinen Aikakauslehti 83 (4): 193-195.

The author discusses the application of root-pruning as a substitute for transplantation, and the experience gained in this respect in

other countries. The method has not been tested in Finland, or anywhere else under the conditions in which seedlings are grown here - on peat moss in plastic greenhouses. The author asks nurserymen to test root-pruning, as it indicates promising aspects, and there exists a great need for a method less laborious than normal transplantation.

(author's abstract)

82. Lamar, R.T. 1982. Effects of root pruning and mycorrhizal inoculation of three species of nursery grown 1-0 bareroot hardwood planting stock. MSc Thesis for Fac. For., Mississippi State Univ., Mississippi State. Mississippi, USA. 71 p.

Seedlings of three hardwood species, cherrybark oak (Quercus falcata var. pagodifolia Ell.), sweetgum (Liquidambar styraciflua L.), and green ash (Fraxinus pennsylvanica Marsh.) were grown in the nursery and subjected to five different root pruning treatments with and without mycorrhizal inoculation. The root pruning treatments included undercutting, undercutting plus late lateral pruning, early lateral pruning, late lateral pruning and control. Cherrybark oak seedlings were inoculated with Pisolithus tinctorius and those of sweetgum and green ash with Glomus fasiculatis. Root pruning had no direct effect on either cherrybark oak or sweetgum because of the small size of the seedlings of these species. However, undercutting of sweetgum seedlings resulted in a significant reduction in root weights and volumes. In general, root pruning treatments reduced stem dry weight, root collar diameter, tap root length, total, tap, and lateral root weights, total, tap and lateral root volumes and number of second order lateral roots of green ash seedlings. Undercutting plus late lateral pruning resulted in the most severe reductions. Green ash seedlings were not affected by early lateral pruning. Significant growth increases due to mycorrhizal inoculations were obtained with all three species. Growth enhancement of cherrybark oak occurred despite a lack of infection by Pisolithus tinctorius or any naturally occurring inoculum. Growth enhancement due to inoculation resulted in significant increases in the number of plantable sweetgum (87%) and green ash (55%) seedlings over noninoculated seedlings. Glomus fasiculatis is suitable for the artificial inoculation of sweetgum and green ash seedlings.

83. Lanquist, K.B. 1965. Side pruner developed at Mount Shasta nursery. U.S. For. Serv. Tree Plant. Notes 70: 3-4.

A side pruner was developed and built based on tests at the Mount Shasta nursery. Cutters that made a clean cut without tearing off the roots were difficult to find so 20 inch coulters were adapted for use. The indentation in the cutter gathers up the roots and cuts them cleanly. The cutters can be adjusted for almost any spacing. The machine is operated by a hydraulic lift at the driver's seat and is mounted under the tractor.

84. Long, J.N. 1978. Root system form and its relationship to growth in young planted conifers. p. 222-234 In E. Van Eerden and J.M. Kinghorn (Eds). Proceedings of the root form of planted trees symposium. Victoria, British Columbia, May 16-19, 1978. B.C. For. Serv./Can. For. Serv. Jt. Rep. No. 8.

Root systems of artificially regenerated conifers growing in Oregon and Washington were excavated four to seven years after outplanting.

Root system form is described for the different species and stock types examined and is compared to that found in naturally regenerated trees of about the same age. Differing root forms resulting from planting methods and nursery culture, including wrenching are described. Five growing seasons after outplanting, wrenched trees had significantly more root system constriction and a higher incidence of L-rooting than unwrenched trees but root/shoot ratios were not significantly different. Overall size and survival, after five years were significantly greater for the trees that had been wrenched. Relationships between root system form and various parameters of above ground development are discussed.

85. Lott, J.R. and R.G. Hallman. 1973. New Zealand root pruner evaluated for U.S. use. U.S. For. Serv. Tree Plant. Notes 24 (4): 18-20.

The New Zealand root pruner is comprised of two separate implements and prunes seedling roots horizontally and vertically on one pass. The horizontal pruning implement, mounted on the hitch, undercuts the seedling bed with a reciprocating blade and the vertical pruner, mounted on the front of the tractor, consists of rolling coulters attached to a frame that can be raised and lowered hydraulically.

The horizontal pruning attachment was tested at 10 nurseries and nurserymen were generally pleased with its performance. Only 4 out of 10 nurseries could test the vertical pruning attachment because of difficulties in mounting the unit on the tractor. The vertical pruning attachment was not considered effective at any of the nurseries where it was tried.

86. Lowman, B.J. 1973. Redesign of horizontal root pruner. USDA For. Serv. Equip. Dev. Center, Missoula, Mont. 5 p.

A discussion of the features of a redesigned undercutting device as developed at the Missoula Equipment Development Center. Plans based on standard American parts are available.

87. Lupke, B. von. 1981. Better field performance of Douglas fir after undercutting in the nursery. Forstarchiv. 52: 10-13. (In German - English summary.)

Two provenances of 2+2 Douglas fir (Pseudotsuga menziesii) were undercut in nursery beds on three dates. Undercutting reduced shoot growth without influencing root weight and thus improved shoot-root ratio (of 7.1-7.9 with controls to 5.3-6.7 with treated plants). Treatment in May had the best effect. The following spring seedlings were outplanted on two plantation areas in northern Lower Saxony. After two years, undercut plants showed a higher survival (82-86% of plants treated in May compared with 48-60% of controls) combined with slightly better height growth. Treatment in May was optimal.

(from author's summary)

88. Mahmood, M.S. 1983. Conditioning of Pinus caribaea Mor. var. hondurensis and Gmelina arborea Roxb. for bare-rooted planting. Thesis for Fac. For., Univ. Pertanian Malaysia, Serdang, Selangor, Malaysia. In Forestry Abstracts 1983.44:224.

Several root wrenching regimes were tested on P. caribaea and G. arborea seedlings to determine the most suitable one to produce a hardened planting stock capable of surviving bare-rooted planting.

Field survival tests were conducted, and results were correlated with physiological characteristics including root regeneration potential (RRP) and plant water status. The five treatments were potted (C), unwrenched (W0), wrenched once (W1), wrenched monthly (W2) and wrenched fortnightly (W4). The survival rates for C, W4, W2, W1 and W0 were 78.75, 68.75, 61.25, 61.25 and 47.50%, respectively. G. arborea seedlings showed 100% survival in all treatments. Frequently wrenched seedlings showed a high root/shoot ratio (for G. arborea), high RRP (for P. caribaea), and better water economy, enabling them to endure more adverse environmental conditions when outplanted in the field.

(author's abstract)

89. Malinovski, J.R. 1977. Metodos de poda radicular em Araucaria angustifolia (Bert.) O. Ktze. e seus efeitos sobre a qualidade de mudas em raiz nua. Revista Floresta 8 (1): 85-88.

Araucaria angustifolia (Bert.) O. Ktze. seedlings were used to study the different variables which indicate the quality of seedlings and which ones show a good relationship with survival percentage. The variables which were studied were height, fresh weight of root and shoot, dry weight of root and shoot, root collar diameter and root length.

The treatments consisted of root pruning at depths of 5, 10 or 15 cm, cutting off the root tip after pregermination and crushing the root tip after pregermination. All treatments stimulated the formation of lateral roots. Root pruned seedlings had vigorous secondary root development at the point of truncation and there was also an increase in secondary roots just below the collar. Root pruned seedlings had more chance of survival when planted out in areas with shallow soils than plants with long tap roots. Seedlings should be root pruned at least once at a depth of 15 cm.

In Brazil, height has been used as criteria for planting but better results can be obtained if root collar diameter, root dry weight and total dry weight are also considered.

90. McCracken, I.J. 1978. Carbon dioxide uptake of pine seedlings after cool storage. For. Sci. 24: 17-24.

During the last half of the growing season, 2-0 Pinus mugo Turra and 1-0 Pinus radiata D. Don seedlings were wrenched weekly using a reciprocating blade wrencher. The seedlings were lifted at varying times and stored for periods of up to 18 weeks. All seedlings were then potted and grown in controlled environment for 6 weeks before being assessed for $CO_2$ uptake and water potential. $CO_2$ uptake was measured using a pulse exposure of individual fascicles to air containing a known proportion of $CO_2$ as $^{14}CO_2$.

Cool storage reduced the rate of $CO_2$ uptake in both species despite water potentials normal for active gas exchange at the time of measurements. Seedlings lifted in spring showed less $CO_2$ uptake than those lifted in midwinter, an effect compounded by storage. Wrenching did not affect $CO_2$ uptake until after the longest storage periods for P. radiata seedlings. In a more intensive examination of seedlings after 18 weeks storage P. mugo showed a steady recovery of $CO_2$ uptake despite initial water potentials of -16 bars, whereas P. radiata was unable to increase $CO_2$ uptake until water potential was above -14 bars. The results suggest that there is disorganization of

the photosynthetic process during storage and that recovery is slowed by low water potential following planting.

(edited author's abstract)

91. McCracken, I.J. 1979. Changes in the carbohydrate concentration of pine seedlings after cool storage. N.Z. J. For. Sci. 9: 34-43.

The changes in carbohydrate concentration in foliage, stem and roots of 2-0 Pinus mugo and 1-0 Pinus radiata seedlings during cool storage and after a subsequent period of growth are examined. Root wrenching was applied to half the numbers of each species in the nursery bed using a reciprocating blade wrencher and maintained at weekly intervals for the latter half of the growing season.

Seedlings were cool stored for 0, 6, 12 and 18 weeks and analysed for carbohydrate (as soluble sugars and starch) on removal from storage and after six weeks subsequent growth in controlled environment.

Concentrations of carbohydrate were highest at lifting (10-14% of seedling dry weight) and declined steadily through 6, 12 and 18 weeks' cool storage in both species. Pinus mugo seedlings retained higher concentrations in stem and root than P. radiata during cool storage and these were depleted during subsequent growth. Pinus radiata showed a similar pattern of depletion during growth following 0 and 6 weeks' cool storage but results suggest that alternative resources were utilized following 12 and 18 weeks storage, resulting in a decline in vigour. A pre-treatment of root wrenching had no significant effect on carbohydrate concentrations in either species.

(edited author's abstract)

92. McKinnon, J.D. and J.H. Nicholson. 1974. Development of a forest nursery on peat land. N.Z. J. For. 19: 122-131.

Investigation into a suitable nursery site to supply tree stocks (mainly radiata pine) for Aupouri Forest, Northland, began in 1963. In 1966, 29.5 ha of peat land was acquired, some 6.5 km south of the Forest headquarters. Development of this site was virtually complete in 1973, much of the work having been of an experimental nature because of lack of local experience in using peat soil for a tree nursery. The various measures taken and their results are described.

Operational practices chosen for this nursery are outlined. The normal conditioning regime is horizontal undercutting at fortnightly intervals and vertical cutting at three to four week intervals. The vertical pruning is done with specially adapted discs.

93. Menzies, M.I. 1980. Effect of nursery conditioning on the water relation of two-year-old Douglas fir seedlings after lifting and outplanting. Ph.D. thesis for Univ. of Washington. 208 p.

Bare-root two-year-old seedlings of Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) were grown in a nursery using conventional techniques or root wrenching and two bed densities. The objectives were to determine the influence of these treatments on morphological and physiological characteristics of seedlings under both controlled and field environments.

Wrenching produced seedlings that were shorter, with a smaller caliper and with desirably lower shoot/root and foliage/root surface area ratios than conventional seedlings. Neither sturdiness nor root system size were significantly altered. Lowering seedbed density did

not significantly alter seedling morphology except in March, when lower density seedlings were sturdier. Wrenched seedlings had lower foliar mineral nutrient levels of N, P and K and also a lower chlorophyll content than conventional seedlings. Pressure-volume curves showed that tops of wrenched seedlings had more negative osmotic potentials initially and at zero turgor. Wrenched seedlings had a better survival at the end of the droughting experiments. Survival of seedlings planted in a field trial exceeded 98% after two years and both wrenched and conventional seedlings had the same average height increment.

(edited author's abstract)

94. Michaud, D. 1984. Effect of cultivation conditions and sorting of plants on the growth of Douglas fir. Ann. Recherches Sylvicoles, AFOCEL 1983: 156-189.

Results of tests concerning the effects of growing conditions and of plant sorting on the growth of Douglas fir (Pseudotsuga menziesii) are presented.

With regard to the growing conditions, plants having been raised under natural conditions often provide the best results. Plants artificially produced in or out of containers may also have a good growing behaviour, provided some quality norms are respected: they have to be particularly well-balanced. Among 3-year-old plants planted out at the end of the first year (plants 1+2) the strongest ones, i.e. those raised at a low density, will get the best results in plantation. The growth of 2-year-old seedlings raised under natural conditions and undercut at the beginning of the second growing year, may be compared to the 3-year-old and planted out seedlings.

Sorting according to heights at the end of the nursery stage results in important growth differences in plantations: for a given plant lot, the bigger plants grow faster than the medium ones, which in turn grow better than the smaller ones. There is also a positive correlation between rooting and height of the plant. In the same way, sorting according to the norms of the National Forest Foundation results in a better growth of initially stronger plants.

(author's abstract)

95. Moberly, B.W.A. 1970. The raising and planting of Pinus radiata seedlings throughout the year. N.Z. For. Serv., For. Res. Inst., Res. Leafl. No. 3. 4 p.

The practicality of planting Pinus radiata seedlings in each month of the year was tested in 1968. A wrenching regime was used to check shoot growth, condition the trees to extremes of both heat and cold, and stimulate fibrous root development. The initial undercut was made at a depth of 2-1/2 to 3 inches, when the seedlings had reached a height of 10 to 12 inches and was followed by fortnightly wrenching and lateral pruning at 6 to 8 week intervals. This regime was maintained until the stock was outplanted. Only two of the 23 plantings, made from January 1968 until January 1969, had survival figures of less than 90%. This was attributed to poor planting technique and the omission of early lateral wrenching. The results of this trial showed clearly the feasibility of both raising and planting 1-1/2-0 Pinus radiata seedlings throughout the year provided the stock is adequately conditioned by regular fortnightly wrenching and that there is minimum delay and careful handling between lifting and planting.

96. Morris, J.W. 1979. Growth and moisture relations of western hemlock seedlings as affected by root or shoot disturbance. M.S. Thesis for Oregon State University. 78 p.

The need for increased efficiency in regeneration of western hemlock (Tsuga heterophylla (Raf.) Sarg.) requires greater understanding of seedling physiology. Experiments examined western hemlock seedling growth responses to in-bed root pruning, and pruning of shoots or roots prior to transplanting. Measurement of plant moisture stress (PMS) after physical root disturbance, and measurement of cytokinin activity in xylem sap were also taken.

Seedlings that were root pruned in the nursery bed initially had decreased root dry weights and increased shoot-to-root ratios. In time, both July and September pruned seedlings tended to match control seedling shoot-to-root ratios. The rate of recovery for the July pruned stock was faster than the September pruned seedlings.

In pruning experiments conducted in both the field and growth chamber, the shoot-to-root ratio was generally uniform among control, root pruned, and top pruned seedlings by the end of the test period. Significant differences did exist between growth environments. Highest shoot-to-root ratios were recorded in the site where moisture stress was probably lowest.

Root pruning and root abrasion generally increased stress level in western hemlock and Douglas fir seedlings compared to controls. However, abraded seedlings had significantly lower PMS levels than controls on the first morning following planting. The hemlock seedlings had generally higher PMS levels than the Douglas fir.

Cytokinin activity in western hemlock xylem sap was negligible from August to early April. A sharp increase in zeatin-like and zeatin riboside-like substances was found in mid April.

These findings suggest that the balance of shoot and root growth is environmentally directed. Moisture stress may play a role in interfacing environmental stimuli and internal metabolism. Acknowledging the role of environmental factors in determining growth patterns, it is suggested that seedlings should be grown for specific cultural conditions.

(author's abstract)

97. Mrazek, F. 1973. Rationalization of forest planting by the use of two-year-old Pinus sylvestris seedlings with undercut root systems. Sozialistische Forstwirtschaft 23 (1): 343-344.

In a comparison in E. Germany of normal 1+1 stock and 2+0 stock that had been undercut 7 cm deep, by spade cuts in an open V, twice in the second year, the undercut stock performed significantly better during the first season after planting. Mechanization of the undercutting is discussed, since the manual process is expensive.

(CAB abstract)

98. Mullin, R.E. 1957. Experiments with root and top pruning of white spruce nursery stock. Ont. Dep. Lands and Forests. Res. Rep. 36. 31 p.

In 1954, 2-1 white spruce (Picea glauca (Moench) Voss) seedlings were subjected to hormone treatments in combination with varying degrees of root and shoot pruning. The effect of these treatments on survival in the nursery and first year survival after outplanting are described.

The hormone powder, containing 0.10 percent indolebutyric acid and 0.25 percent alphanapthylacetic acid in talc, had no effect upon survival of stock in the field. It may have an effect on later growth.

Top pruning, in the degree used, had no effect by itself upon survival in the nursery or in the field.

The relationship for root pruning is more involved as a greater variety of treatments were tested. It was found that the Heavy (One and one-half inches) was detrimental, the Moderate (three inches) was ineffective and the machine root pruning (four and one-half inches) was beneficial to survival in the nursery. Repeating the root pruning had no measurable effect upon survival in the nursery. Conversely to the nursery effects, the root pruning treatments appear by themselves to have no measurable influence on survival in the field.

The combinations of root and top pruning appear in some instances to be effective both on survival in the nursery and in the field. As far as nursery survival is concerned, no combination of top pruning with moderate, heavy or repeated root prunings appeared to have an effect on survival and, therefore, it was of no benefit to the nurseryman in this respect. Machine root pruning and top pruning materially reduced nursery survival.

In survival in the field, the combination of top pruning with a moderate root pruning (three inches) has produced the highest survival, greater than the control. Survival was further increased by repeating the root pruning later in the growing season. Machine root pruning at the depth used appeared ineffective.

We may conclude, therefore, that a moderate root pruning coupled with top pruning should be considered for 2-2 white spruce, when done at the 2-1 stage. This appears to do no harm to nursery survival and increases field survival. The operation would also tend to produce stock of a more uniform size for shipping.

(edited author's abstract)

99. Mullin, R.E. 1966. Root pruning of nursery stock. For. Chron. 42: 256-264.

In the fall of 1958, an experiment was begun at Midhurst Nursery to study the effects of root pruning at different stages of growth and at two depths, on 3-0 stock of white spruce (Picea glauca (Moench) Voss) and white pine (Pinus strobus L.). Root pruning was done by undercutting broadcast-sown seedbeds at two inch and four inch depths; in the fall as 2-0 (Sept. 16, 1958), in the spring at start of growth (April 30, 1959), during flush of growth (May 28, 1959) and towards end of terminal growth (June 25, 1959).

Seedbed counts were taken before lifting, in fall 1959, to study mortality. Random samples were taken on date of lifting (Sept. 17, 1959), for laboratory measurements to study effects on seedling size. Other random samples were planted in experimental designs at Larose Forest. Counts of survival, and measurements of terminal growth were taken at the first, third and fifth year after planting.

Results showed no mortality in the nursery but that all root pruning reduced height growth. Root pruning of white spruce after the flush of growth (June 25) increased survival and growth after outplanting, over that of unpruned stock. None of the treatments increased survival or growth of white pine. Depth of root pruning had no significant effect.

(author's abstract)

100. Mullin, R.E. and R.E. Hutchison. 1979. Seedbed treatments to aid in fall lifting for frozen overwinter storage. Ont. Min. Nat. Res. Nursery Notes No. 64. 4 p.

In 1973, an experiment with 3+0 red pine (Pinus resinosa Ait.) seedlings was started to examine treatments which might induce hardening or delay surface freezing. The four treatments were a control with no treatment, a sawdust mulch, a suspended plastic cover and root pruning at a depth of 8-10 cm done on October 16 and October 25. The seedlings were lifted and placed in frozen overwinter storage. Five years after outplanting measurements of survival, total heights and terminal growth were obtained. Trees treated with repeated root prunings had increased survival.

101. Nambiar, E.K.S., G.D. Bowen and R. Sands. 1979. Root regeneration and plant water status of Pinus radiata D. Don seedlings transplanted to different soil temperatures. J. Exp. Bot. 30: 1119-1131.

The regeneration and configuration of new roots on transplanted 8 month old Pinus radiata D. Don seedlings were measured in relation to soil temperature and time after transplanting. The effects of root wrenching and nutrition on root regeneration were compared. Low soil temperature adversely affected the initiation and elongation of new roots. The branching and morphology of the new roots were also influenced by soil temperature. The processes of initiation and elongation are greatly retarded below a critical root temperature between 11 and 14°C. Wrenching and fertilization stimulated new root growth at low temperatures. There is a close interrelationship between the constituent parts of the network which forms the new root system. The first-order laterals on transplants are critical as a basic framework for extension and production of second-order laterals which form the major part of the regenerating root system.

Needle water potential was closely related to the new root growth. The water stress experienced by the transplants for several weeks after planting was due primarily to the suppressive effect of low soil temperature on root regeneration. Wrenched plants were less water-stressed than unwrenched plants.

Field measurements confirmed the finding from controlled experiments that, in southern Australia, the low soil temperature in the planting season imposes a major restriction on early root regeneration which in turn inflicts water stress in transplants. This needs to be considered during the planning of planting and fertilization.

(authors' abstract)

102. Nambiar, E.K.S. and P.G. Zed. 1980. Influence of weeds on the water potential, nutrient content and growth of young radiata pine. Aust. For. Res. 10: 279-288.

The effects of weed control on subsequent weed growth and on the needle water potential, nutrient uptake and growth of young radiata pine (Pinus radiata (D. Don) during the months after transplanting were examined under two contrasting environments typical of the southeastern region of South Australia. Two seedling types (wrenched or unwrenched) were used. Wrenching was done 3 times by making a spade cut 10-12 cm from each side of the row and angling the cuts to meet at a vertical depth of 15 cm below the surface of the soil.

Despite unusually high November rainfall during the experiments, pines in weedy plots were severely water stressed by early January, having very low needle water potentials which persisted until early April. Drought, induced by weeds, caused up to 40% mortality in transplants. Weed growth also reduced the nutrient concentration in the needles. Complete weed control resulted in 10- to 140-fold increases in stem volume, depending on the site, 17 months after transplanting.

Root wrenching had little effect on the performance of outplanted stock, nor were there any significant interactions between weed control treatments and wrenching in any of the parameters measured. Inadequate intensity of wrenching and lack of stress to the seedlings during lifting, transporting and planting may have contributed to the lack of effects from wrenching.

Application of moderate amounts of Atrazine and Amitrole resulted in a relative dominance of sorrel (Rumex angiocarpus) over grass and other re-emerged weeds. Such changes in botanical composition of weed cover directly influenced the needle water potential in pines. Percentage cover and specific composition of weeds may be useful measures to assess the degree of drought likely to be experienced by young pines.

(edited authors' abstract)

103. Olson, D.S. 1930. Growing trees for forest planting in Montana and Idaho. USDA Circular No. 120: 45-53.

Underground pruning alone is not an adequate substitute for the more expensive operation of transplanting because the broadcast method of sowing seed does not give a uniform spacing of plants. At Savenac nursery, root pruning is only done when there is an overproduction of stock that cannot be transplanted or shipped. The only species root pruned are western white pine, western yellow pine and western larch.

The year old stock is horizontally pruned with a flat steel blade, 1/4 inch thick, which is mounted on wheels and pulled through the beds by a horse. Two-year-old stock is pruned with a thin flat blade attached to a Smith digger. This implement is pulled along with a cable wound around a capstan revolved by one horse. The beds which are sprinkled before and after root pruning are pruned at a depth of four inches.

104. Owens, J.N., J.E. Webber, S.D. Ross and R.P. Pharis. 1985. Interaction between gibberellin $A_{4/7}$ and root pruning on the reproductive and vegetative process in Douglas fir. III. Effects on anatomy of shoot elongation and terminal bud development. Can. J. For. Res. 15: 354-364.

The relative importance of cell division and cell elongation to shoot elongation and the anatomical changes in vegetative terminal apices were assessed for 9- and 10-year-old seedlings of Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) in response to two effective cone-induction treatments, gibberellin $A_{4/7}$ ($GA_{4/7}$) and root-pruning (RP). Root-pruning was done in mid-April at the start of vegetative bud swelling and GA treatments were begun at vegetative bud flushing in mid-May and continued until early July. Shoot elongation before flushing resulted primarily from cell divisions and was not affected by the RP treatment. Shoot elongation after flushing resulted primarily from cell expansion which was reduced by RP treatments. Root-pruning significantly slowed mitotic activity,

apical growth, and development of vegetative terminal buds from mid-June through mid-July. Apical growth then resumed during leaf initiation and the final number of leaf primordia initiated was not affected. This resulted in a delay of 2 to 4 weeks in the transition from bud-scale to leaf initiation. Retarded terminal vegetative apices anatomically resembled latent axillary apices but were never completely inhibited. GA + RP had the same effect as RP. $GA_{4/7}$ alone had no effect on shoot or apical development. These results show that RP and GA + RP significantly retard shoot elongation and terminal bud development but still allow normal development of vegetative terminal buds. Retardation of bud development by a few weeks shifts the critical morphogenetic phase of transition from bud scale to leaf initiation to a later time when endogenous and environmental conditions may differ from the normal.

(authors' abstract)

105. Parviainen, J. 1976. Root pruning in the nursery and at planting - a study based on literature. Folia For. 267: 1-26.

Reports published on the pruning of bare root seedlings in the nursery and at planting are reviewed. The purpose was to compile available information on root pruning, which is relevant in Finnish conditions. The first part reviews the biological basics of root pruning. Effects of pruning on seedling root systems are also described.

Plant roots can be pruned in connection with four handling phases. Roots can be pruned to substitute for transplanting. This method of plant growing (precision sowing - root pruning - plant lifting) can be highly mechanized to save in labour and costs. The review covers the method of pruning, its time, distance and equipment, growing density and results of research on the planting of pruned seedlings.

The roots can also be pruned before transplanting, when growing very large plants, and before planting. These pruning activities are primarily examined from the biological point of view; results of planting tests with root-pruned plants are also shown.

(edited author's abstract)

106. Parviainen, J. 1981. Root pruning as a cultivation method for bare-root pine seedlings. Translation Environ. Can., No. OOENVTR-2039. 14 p. (Parviainen, J. 1980. Juurten leikkaaminen männyn paljasjuuristen taimien kasvatusmenetelmänä. Comm. Inst. For. Fenn. 98 (2): 1-131.)

The biological aspects of root pruning as a cultivation method for bare-root pine seedlings and its application in Finland were examined. Root pruning resulted in immediate disturbance in the water absorbing capacity of seedlings. The season of pruning affected height growth, shoot base diameter, root-shoot ratio and new root growth. The more severely the roots were pruned, the smaller the needle length, seedling base diameter and shoot dry weight was. The root system was more compact and the number of new roots was higher with the more severe root pruning. Severe pruning with manual tools resulted in the needles of seedlings turning yellow, probably due to disturbed nutrient uptake.

Seedbed density had a strong effect on growth of the base diameter and production of dry matter. Root-shoot ratio, the number and length of secondary roots and base diameter-height ratio of seedlings all increased with increased growing space. During the first growth period after planting, root-shoot ratios underwent the greatest change in unpruned seedlings.

107. Parviainen, J. 1982. Neue möglichkeiten bei der Anzucht wurzelnackter Forstpflanzen. Allgemeine Forst Zeitschrift No. 1/10: 247-249.

Three Scots pine (Pinus sylvestris L.) stock types, control (2+0), transplants (1+1) and transplanted (1+1) with undercutting in the second year, were evaluated for ease of production, morphology and field performance. Transplanting too early resulted in lammas shoots while transplanting too late resulted in losses in the beds.

Undercutting was done with a j-shaped knife at a distance of 4-5 cm from the row of trees at a depth of 6 cm on one side and three to four weeks later on the other side. Optimal density was 50 plants per lineal meter of bed which produced a cull rate of 20 percent.

Transplanting and undercutting produced a more fibrous root system and a more favourable root to shoot ratio. The control trees grew considerably poorer than trees which were undercut. Height growth was best for the transplants, followed by the undercut transplants and then the controls.

108. Petäistö, R-L. 1982. Risk of fungal infection on coniferous seedlings after root pruning in forest nurseries. Folia For. 505: 1-8.

The risk of fungal infection after root-pruning was investigated in two nurseries, of which one used peat as substrate and the other used a mineral soil. The experiments were carried out with both pine and spruce. Root-pruning was performed in the nursery bed at three different times. The fungi appearing on the pruning wounds were investigated one and two months after pruning as well as in spring the following year. Fungi mainly belonging to the genera Fusarium, Cylindrocarpon and Trichoderma, and one unidentified, dark non-sporulating fungus, were isolated from the pruning wounds. The pathogenicity of Fusarium and Cylindrocarpon fungi was tested on young seedlings.

The Fusarium and Cylindrocarpon genera were more common in the mineral soil nursery than in the nursery where peat was used. The antagonistic Trichoderma genus and the unidentified dark fungus were most frequently isolated from the nursery where peat was used. Fungi of the Cylindrocarpon genus occurred more often in pruning wounds of pine than of spruce. There was no difference between pine and spruce with respect to the other fungi.

The risk of fungal infection was greater in the mineral soil nursery than in the one using peat. At the nurseries included in the experiments at least no remarkable risk for fungal infection after pruning could be observed.

(author's abstract)

109. Proshin, N.S. 1982. The effect of root pruning on the quality of Scots pine seedlings. Lesn. Khoz. No. 4: 27-28.

A note on experience in root pruning (undercutting) Scots pine (Pinus sylvestris L.) seedlings to produce a compact fibrous root system. Data are tabulated on the dimensions of seedlings (3-4 yr old) given 0-4 root prunings. Seedlings should not be root pruned more than 1-2 times during the growing season nor late in the season. Root pruning should be done only on older seedlings (3-4 yr old) that are sparsely and uniformly distributed in seedbeds.

110. Riedacker, A. 1976. How to modify root morphogenesis of some young seedlings and its practical importance. p. 376-387 In 16th IUFRO World Congress, Div. 1, Norway, 1976.

The predominance of the apical root meristem in the root system morphogenesis is shown experimentally. Speed of growth and direction of lateral roots are determined sometimes irreversibly at a very early stage (1-2 weeks).

To modify the morphogenesis of a root system it is therefore necessary to cut off or decrease the effect of this meristem sometimes immediately after germination. Results vary however with the species; a few lateral roots may replace the tap root; new roots may regenerate from the cut end, etc. Practical means to modify root morphogenesis are indicated and the possible benefits of such modifications are discussed.

111. Röhrig, V.E. 1977. Undercutting of oak seedlings. Forstarchiv. 48: 25-28. English summary.

During the vegetation period 1975 the influences of root pruning on the growth of 2-year-old oak seedlings in a nursery were measured.

The roots of the oak seedlings were undercut at the following dates: June 6, June 6 and 26, June 26 and July 17.

Shoot length and dry weight of leaves, shoots and roots are strongly reduced by the root cutting. The shoot-root-relation was influenced (in favour of the shoot) only at the latest date.

The contents of nitrogen, potassium, calcium and magnesium of the treated plants were lower than those of the control. Probably these effects could be changed by fertilization.

Undercutting improves the lateral rooting of the seedlings.

(edited author's abstract)

112. Rook, D.A. 1969a. Studies on the physiology of wrenched seedlings. p. 119-121 In Forest nursery and establishment practice in New Zealand. N.Z. For. Serv., For. Res. FRI Symp. No. 9.

Only tentative and incomplete results were available for this experiment on the changes in physiology and morphology of wrenched Pinus radiata seedlings because the experiment was still in progress. Fifteen month old seedlings which had received one of three treatments, no wrenching, wrenched once 5 months previously;, and wrenched fortnightly over a 5 month period, were tested in a simulated drought environment for 7 days. The fortnightly wrenched plants had the highest transpiration rates and no morphological effects of drought while the unwrenched seedlings were severely wilted and had the lowest transpiration rates.

113. Rook, D.A. 1969b. Water relation of wrenched and unwrenched Pinus radiata seedlings on being transplanted into conditions of water stress. N.Z. J. For. 14 (1): 50-58.

Internal water deficits and rates of transpiration of 15 month old Pinus radiata seedlings which had been unwrenched (C), root wrenched once (W/1), or wrenched at fortnightly intervals over the previous five months (W/F) were compared for seven days after being transplanted into conditions of water stress in a controlled environment cabinet. Relative turgidities of the needles of the seedling pretreatments were ranked in the order W/F > W/1 > C. Rates

of transpiration of the W/F seedlings were significantly higher than those of the seedlings of the other two treatments. Differences in rates of transpiration between detached shoots of the three treatments were slight; those of the W/F seedlings had the highest rates. Seven days after the seedlings were transplanted the root systems of only the W/F stock showed many new roots. Results from this investigation support those from field trials which indicate that well-wrenched transplants survive dry conditions better than W/1 plants, and even more so than C plants, owing in part at least to the effect of repeated wrenching in producing a root system more capable of meeting the requirements of the plant after transplanting.

(author's abstact)

114. Rook, D.A. 1971. Effect of undercutting and wrenching on growth of Pinus radiata D. Don seedlings. J. Appl. Ecol. 8: 477-490.

The purpose of the study was to describe and measure the effects of different intensities of wrenching and the effects of undercutting and wrenching at different times of the year on the growth of Pinus radiata seedlings. Treatments for the first trial, started in December were control (W/0), undercut and wrenched weekly (W/1), fortnightly (W/2), and monthly (W/4). Two more trials, started in March and May, used only the W/0 and W/2 treatments. All trials lasted for three months.

In the first trial, undercutting and wrenching stopped almost all shoot growth and significantly reduced rates of net assimilation, but relative growth rates were unaffected. Intensity of wrenching had only a minor effect on reducing shoot growth but had a marked effect on the carbohydrate reserves of the plants. Undercutting and wrenching caused a three-fold increase in the relative flow of C-assimilates from the foliage to the roots and produced planting stock with only a small amount of soft new shoot growth, a high shoot/root ratio and a compact mass of fibrous roots.

Neither of the two later trials, March and May, produced fully conditioned stock. The seedlings were not only photosynthesizing less rapidly but a smaller proportion of the plant's total photosynthate was being translocated to the roots.

115. Rook, D.A. 1973. Conditioning of planting stock. N.Z. For. Serv., Rep. of For. Res. Inst. 1972: 44.

In treatments to produce well conditioned seedlings the infuence of drought stress after undercutting is now thought to be less important than the role of hormones produced by the tips of the actively growing roots: the better planting stock obtained from shallow (as compared to deep) undercutting and wrenching probably results from removing a larger number of growing root-tips. Seedlings undercut and wrenched at two weekly intervals performed better than seedlings conditioned by other treatments, after transplanting into three soils at four different temperatures in a controlled environment.

(CAB abstract)

116. Ross, S.D., J.E. Webber, R.P. Pharis and J.N. Owens. 1985. Interaction between gibberellin $A_{4/7}$ and root pruning on the reproductive and vegetative process in Douglas fir. I. Effects on flowering. Can. J. For. Res. 15: 341-347.

In two seed orchard trials, profuse female flowering was induced in young, but ontogenetically mature grafts of inherently poor-flowering clones (1979) and in 9-year-old seedling-origin trees of both good- and poor-flowering families (1981) of Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) by the cultural treatment of root-pruning in conjunction with stem injections of the gibberellin $A_4$ and $A_7$ ($GA_{4/7}$) mixture. Promotion of male flowering, however, was confined to the more sexually mature grafts. As an individual treatment in the 1981 study, root-pruning was more effective than $GA_{4/7}$, particularly for the poor-flowering families which did not respond well to $GA_{4/7}$ alone. The two treatments combined had a highly synergistic effect on both male and female flowering, the synergism being relatively greater for the poor-flowering than for the good-flowering families. Although $GA_{4/7}$ was not tested alone on grafted propagules, its use with root-pruning enhanced an already significant increase in seed- and pollen-cone buds from root-pruning alone by 540 and 92%, respectively. These and subsequent trials have shown root-pruning + $GA_{4/7}$ to be a most effective cone-bud enhancement treatment for use in young Douglas fir breeding and seed production orchards.

(authors' abstract)

117. Shea, G.M. and P.A. Armstrong. 1978. Factors affecting survival in open-root plantings of Caribbean pine - coastal Queensland. Dep. For. Queensl., Tech. Pap. No. 8. 18 p.

Results of experimental open-root plantings of Caribbean pine (Pinus caribaea var. hondurensis Barr. and Golf.) established in coastal southeastern Queensland and at Bowenia since 1969 were examined to determine the factors influencing survival with the object of making recommendations for large scale plantings.

Survival of hand wrenched, hand planted stock was related to wrenching interval, number of wrenchings applied, seasonal conditions and varied from planter to planter. Wrenching interval, number of wrenchings and seasonal conditions had less effect on survival of mechanically wrenched, machine planted stock for the range of wrenching intervals used. Wrenching depth had little effect on survival.

Survival was strongly influenced by stock quality and cull rate was strongly influenced by nursery bed density. Survival was similar for summer and winter plantings in southeastern Queensland. At Bowenia, satisfctory survivals were obtained from December to March plantings. Survival at Bowenia was significantly related to total rainfall one month pre-plant plus one month post-plant.

A clay slurry root dip substantially improved survival in southeastern Queensland but results at Bowenia were variable. Topping can be carried out safely and may have practical application. Chemical conditioning improved survival only slightly. Survival was reduced in plantings on ash heaps or subject to competition from molasses grass. Current extraction and dewinging procedures are harmful to Caribbean pine seed.

(edited authors' abstract)

118. Shipman, R.D. 1958. Planting pine in the Carolina sandhills. USDA For. Serv. Southeast Station Paper No. 96: 12-13.

Root pruning in mid-season (July) of the first year improved longleaf pine (Pinus australis Michx. F.) seedling survival. At all seedbed

densities, ten, twenty or forty seedlings per square foot, the root pruned seedlings had higher survival rates than unpruned seedlings. Root pruned seedlings grown in high bed densities had a lower survival percentage than root pruned seedlings grown in lower bed densities.

119. Shoulders, E. 1959a. Root pruning boosts longleaf survival. U.S. For. Serv. South. For. Notes 120.

Studies in Alexandria, Louisiana found that a single pruning, either shallow (3 to 4 inches below the surface of the bed) or deep (6 to 7 inches), whether done in June, August or November, improved first year survival of longleaf pine (Pinus palustris Mill.) over that of unpruned stock planted on the same sites. Double pruning (shallow in June, followed by deep in November) gave the best survival of seedlings. The most practical technique may be a single deep pruning, two to three months before lifting time.

120. Shoulders, E. 1959b. Root pruning boosts longleaf survival. U.S. For. Serv. Tree Plant. Notes 36: 15-19.

Three studies in 1955, tested the survival of planted longleaf pine (Pinus palustris Mill.) seedlings which had been root pruned in the nursery beds. In the first study, seedlings grown at two bed densities (18 and 27 per square foot) were root pruned at a depth of 6 to 7 inches in early November. Another study compared survival of stock root pruned in November and lifted from the beds with three degrees of care, ranging from normal practice to careful hand lifting. The third study compared the effects of time and depth of pruning. Stock was root pruned in mid-June, mid-August, and mid-November at depths of 3 to 4 inches or 6 to 7 inches. Double pruning was tested by pruning the roots in June at the shallow depth of 3 to 4 inches followed by a deep pruning at a depth of 6 to 7 inches in November.

Root pruning in November benefited stock grown at both bed densities but root pruning was most effective in high density beds or when stock was planted on adverse sites. Root pruned longleaf seedlings require no special care in lifting to preserve their higher survival potential. All combinations of pruning depth and time boosted first-year survival of seedlings significantly when compared to unpruned seedling survival. Differences between pruning treatments were insignificant except for the double pruning treatment which resulted in a higher survival rate. The advantage of late season pruning at a depth of 7 inches is that there is little regrowth of roots and seedling roots do not need to be clipped at grading or planting.

121. Shoulders, E. 1960. Should pines be root-pruned in nursery beds? U.S. For. Serv. South. For. Notes No. 127.

Different lots of longleaf (Pinus palustris Mill.), loblolly (Pinus taeda L.) and slash pine (Pinus elliottii Engelm.) seedlings were pruned once at a depth of 7 inches, monthly between September and January. None of the prunings significantly affected the average height of the stock or checked unwanted late season height growth. This lack of response may be due to differences in soil, time of pruning, seedling size at time of pruning, pruning techniques or weather after pruning.

122. Shoulders, E. 1963. Root-pruning southern pines in the nursery. U.S. For. Serv. Res. Pap. SO-5. 6 p.

A series of seven studies was conducted from 1955 to 1960 in Louisiana to determine the effect of root pruning on yield and field survival of plantable seedlings of longleaf (Pinus palustris Mill.), slash (Pinus elliottii Engelm.), and loblolly (Pinus taeda L.) pine. The treatments were replicated in both the nursery and field phases of all studies. Two studies showed that root pruning is effective over a range of nursery bed densities and that no special techniques are required in lifting and handling stock.

123. Shoulders, E. 1965. Root pruning in southern pine nurseries. U.S. For. Serv. Tree Plant. Notes 70: 12-15.

This article synopsizes results and current recommendations of individual experiments which were reported in U.S. Forest Service Research Paper SO-5 without reference to specific studies.

124. Sluder, E.R. 1964. Quality of yellow-poplar planting stock varies by mother-tree and seed bed density. U.S. For. Serv. Tree Plant. Notes 65: 16-19.

The effects of seedbed density, seedbed root pruning and seed origin on root collar diameters and survival of yellow poplar (Liriodendron tulipifera L.) seedlings were examined. Roots of half of the seedlings from each of the eight mother trees were pruned in the nursery bed at a depth of 8 inches. Variable germination produced plots ranging in density from 4.7 to 27.2 seedlings per square foot. High seedbed densities produced many seedlings with a small root collar diameter which were not plantable. The root pruning treatment had no effect on seedling size distribution or on first year survival. Seedling quality varied significantly with mother tree.

125. Stein, W.I. 1978. An integrated study of nursery stock conditioning: preliminary observations on stock performance. p. B96-B105 In Conference and Workshop Proceedings of the Western Forest Nursery Council and Intermountain Nurserymen's Association, Aug. 7-11, 1978. Eureka, Calif.

Relationships between several nursery cultural practices and subsequent field survival and growth of 2+0 Douglas fir (Pseudotsuga menziesii) seedlings on different sites are being investigated. Results of an exploratory study indicate that both wrenched and unwrenched seedlings increased substantially in stem diameter and root dry weight after early August, that by early winter they were nearly the same size, and that an early August wrenching did not improve their first-season field survival or height growth.

In the larger follow-up investigation, some observations on frost damage at different seed bed densities, chilling requirements, and relationships between nursery cultural practices and mid-season first-year survival are reported. The preliminary data on seedling survival did not appear to be strongly related to nursery cultural practices and the final results might be quite different. Efforts to learn about the combined effects of nursery practices on seedling field performance are continuing.

(edited author's abstract)

126. Stein, W.I. 1984. Wrenching Douglas fir seedlings in August: Immediate but no lasting effects. U.S. For. Serv. Res. Pap. PNW-317. 12 p.

Effects of wrenching Douglas fir (Pseudotsuga menziesii) seedlings in August of their second season in the D.L. Phipps State Forest Nursery, Elkton, Oregon, were determined by periodic samplings to learn of changes in phenological, morphological, and growth characteristics. Initial effects of wrenching moderated by January when seedlings were lifted; both wrenched and unwrenched seedlings had grown substantially larger. Survival and growth of seedlings were good during the first 5 years after outplanting in droughty skeletal soil on southeast and northeast slopes in the South Umpqua River drainage of southwestern Oregon, and no significant differences were found between wrenched and unwrenched seedlings. A difference in total tree height on the two slopes was caused by greater browsing on the southeast slope.

(author's abstract)

127. Stein, W.I. 1985. Effects of wrenching Douglas fir seedlings in August. p. 122-125 In Proceedings of Western Forest Nursery Council - Intermountain Nurserymen's Association Meeting, Aug. 14-16, 1984. USDA For. Serv. Gen. Tech. Rep. Int-185.

Effects of wrenching Douglas fir (Pseudotsuga menziesii) seedlings in August of their second season in the D.L. Phipps State Forest Nursery, Elkton, Oregon, were determined by periodic samplings to learn of changes in phenological, morphological, and growth characteristics. Initial effects of wrenching moderated by January when seedlings were lifted; both unwrenched and wrenched seedlings had grown substantially larger. Survival and growth of seedlings were good during the first 5 years after outplanting, and no significant differences were found between unwrenched and wrenched seedlings.

(author's abstract)

128. Stephens, G.R., Jr. 1964. Stimulation of flowering in eastern white pine. For. Sci. 10: 28-34.

Fertilization of Pinus strobus L. with ammonium sulfate at the rate of 0, 18, 53 and 158 pounds of N per acre, root pruning at a depth of 14 to 16 inches in a four foot radius, and strangling and girdling of branches were tested for inducing and stimulating flowering. Neither ferilizer nor mechanical injury induced flowering in 3- to 14-year-old trees. All treatments except strangling stimulated production of ovulate strobili in 22-year-old trees, but none increased the number of flowering trees. Girdling stimulated production of strobili on individually treated branches. Treatment in July 1959, stimulated production of ovulate strobili in 1960, whereas treatment in April 1960, did not. Treatment in the summer of the year prior to flowering increased the yield of strobili when production would have otherwise been low; no increase was apparent when production was generally high. Stimulation did not persist into a second season.

(edited author's abstract)

129. Stockley, G.H. 1969. Problems and techniques in raising 1/0 Pinus radiata stock in Milton nursery. N.Z. J. For. 14: 159-162.

Production techniques for raising 1-0 Pinus radiata seedlings at the Milton Nursery are outlined. Root pruning is usually done late in March when seedlings have attained the minimum acceptable height growth of six inches. Local trials with beds wrenched progressively from mid-summer onwards, showed clearly that all growth ceases after root pruning so in order to achieve height growth, wrenching must be delayed. A prominent side effect in all wrenching trials, irrespective of date, was a rapid loss of colour within a week or so of wrenching.

130. Stoeckeler, J.H. and G.W. Jones. 1957. Forest nursery practice in the Lake States. USDA For. Serv. Agric. Handbook No. 110.

Forest nursery practices in the Lake States are presented. Specifications and evaluations of root pruners are given and recommendations are made for the use of particular pruners. Results of trials with horizontal and vertical root pruning techniques are described and prescriptions for better field survival are presented. Specific reference is made to pruning treatments as a substitute for transplanting. (Root wrenching on p. 37, 75-78, 103-104.)

131. Stoeckeler, J.H. and P.E. Slabaugh. 1965. Top and root pruning. p. 40-41 In Conifer nursery practice in the Prairie-Plains. USDA For. Serv., Agr. Agric. Handbook 279.

Top and root pruning are used in Prairie-Plains nurseries to retard excessive top growth and keep the trees in better balance. Root pruning of seedlings and transplants is also done in the beds prior to lifting as a preparation for transplanting or packing. To cut nursery production costs, root pruning of seedling stock in place has been recommended as a substitute for transplanting in areas of better rainfall but it has not been tested very much in the drier Prairie-Plains area.

132. Stubbings, J.A. 1958. Raising and use of large close-rooted transplants for commercial afforestation in Southern Rhodesia. J. South Afr. For. Assoc. 32: 36-54.

Under summer rainfall conditions prevailing on a Forestry Estate in the Melsetter district of Southern Rhodesia, particularly in the rank weed and grass growth described, comparatively extensive afforestation of 19,500 acres during the past five years has indicated that large (15" to 20" tall), close-rooted transplants (i.e. a tree planted with a ball of original seedbed soil attached to its roots) preferably planted early in a season, are vastly superior to conventionally-used smaller transplants, are preferable to open-rooted transplants, and are cheaper than pot-transplants.

Nursery practice is described for raising on a large scale these transplants of mainly P. patula, P. elliottii, P. taeda, E. saligna and E. maculata; many other species having also been successfully raised by the method described. Pricking-out of seedlings of species having large seeds (e.g. all the above-mentioned species except E. saligna), is obviated by in situ sowing of individual seeds at the desired 2" x 2" espacement in prepared seedbeds. Species with fine seed, such as E. saligna, are broadcast-sown then pricked-out at the desired espacement into prepared seedbeds. Raised, and preferably revetted seedbeds, 5" to 6" deep and of width equal to that of two boxes holding 40 transplants in five rows of eight transplants each,

are used to facilitate root-pruning and boxing. The necessity for sowing under local conditions, Pine species 12 to 15 months, and Eucalyptus species 10 to 13 months before their transplants are required, and the necessity for regular root-pruning and, in the case of Eucalyptus species, crown-clipping in order to produce sturdy transplants of the desired size, are stressed.

Equipment used for sowing, root-pruning and boxing, and their methods of use are described and illustrated.

The method and results of planting these large close-rooted transplants in the afforestation of the Estate are illustrated and briefly discussed.

(author's abstract)

133. Stupendick, J.T. and K.R. Shepherd. 1979. Root regeneration of root-pruned Pinus radiata seedlings. I. Effects of air and soil temperature. Aust. For. 42: 142-149.

Effects of air and soil temperatures on the regeneration of roots of P. radiata D. Don seedlings following a single root-pruning to a length of 21 cm was examined under controlled conditions. Root regeneration is favoured by air temperatures in the range 20° to 30°C where soil temperature corresponds to ambient air temperature. When soil temperature is controlled independently of ambient air temperatures, low and high soil temperatures do not favour root growth irrespective of the air temperature. The most favourable temperatures for root growth are similar to those for growth of the seedling as a whole. Root morphology changes markedly with soil temperature, from thick, white, brittle roots at low temperatures to thin, flexible, suberized roots at higher temperatures. The implications of the results to some aspects of silvicultural practice are discussed.

(authors' abstract)

134. Stupendick, J.T. and K.R. Shepherd. 1980. Root regeneration of root-pruned Pinus radiata seedlings. II. Effects of root-pruning on photosynthesis and translocation. N.Z. J. For. Sci. 10: 148-158.

The effects of root pruning on photosynthesis and other physiological processes in Pinus radiata D. Don seedlings were examined and related to the observed progress of root regeneration. The seedling roots were extended and pruned at a specified length from the cotyledon, usually 21 cm. During the experimental period seedlings were maintained in an artificially-lit growth cabinet.

Root-pruning of the seedlings resulted in a sharp increase in stomatal resistance and a concurrent drop in net photosynthesis. Eight days after root-pruning leaf water potential was restored to pre-pruning levels and within 12 days photosynthesis showed signs of recovery, accompanied by a decrease in stomatal resistance. Proliferation of new roots took place and thereafter the recovery process intensified. By day 32 photosynthesis was restored to about 60% of the initial rate prior to root-pruning. Translocation of $^{14}C$ assimilate was restricted by root-pruning. An hypothesis concerning the physiological processes involved in root-pruning and hardening of nursery stock is discussed.

(edited authors' abstract)

135. Sutton, R.F. 1967. Influence of root pruning on height increment and root development of outplanted spruce. Can. J. Bot. 45: 1671-1682.

The separation of terminology for root pruning and undercutting is suggested. Root pruning should refer to the clipping of generally naked roots after lifting, mainly for convenience in handling. Undercutting should refer to the severance of roots of plants *in situ*.

136. Sutton, R.F. and R.W. Tinus. 1983. Root and root system terminology. For. Sci. Monogr. 24. 137 p.

Working definitions for wrenching, undercutting, root pruning and side pruning are presented. An attempt at standardizing terminology is made.

137. Sweet, G.B. and D.A. Rook. 1972. Inhibitor levels associated with growth in seedlings of *Pinus radiata*. New Phytol. 72: 1107-1111.

The conditioning of *Pinus radiata* D. Don seedlings to withstand transplanting stress involves the use of a mechanical root undercutting technique. Seedlings were undercut at a depth of 7.5-10 cm and wrenched at two week intervals. Using the Avena coleoptile bioassay, the differences in hormone levels in acidic extracts of the shoots and roots of conditioned and control seedlings were determined. Conditioned seedlings had roots with higher relative growth rates and lower levels of inhibitors per unit of root weight than non-conditioned seedlings.

(edited author abstract)

138. Szemeredy, M. 1972. Concerns of coniferous seedling production in the state forest enterprise of Felsotisza. Erdo 21 (5): 193-199.

The State Forest Enterprise of Felsotisza has to produce 70 million coniferous seedlings in this Five-Year-Plan period. Since in this region mainly transplants are to be used for plantations, the extraordinarily labor-consuming transplantation of the seedlings is a very heavy task. To ease this burden seedling production with root-undercutting has been introduced. The undercut and properly thinned seedlings are as good for plantation as the transplanted ones. Sowing furrows, previously with a distance of 10 centimeters, are recently made 20 cm, respectively 45 cm from another. Undercutting is carried out by machines as well. The new technology proved to be effective and economical.

(author's abstract)

139. Tanaka, Y., A.J. Long and J.K. Winjum. 1974. Effects of undercutting and wrenching on 2+0 Douglas fir seedlings. p. 60-71 *In* Proceedings of Western Forest Nursery Council Meeting, August 6-8, 1974, Portland Oregon.

2+0 Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedlings underwent two undercutting and wrenching regimes: 1/ undercutting at 3" (April) and 4" (June) depths followed by biweekly wrenching at 6" ($U_{3+4}$ + $W_{14}$); and 2/ 6" (April) undercutting followed by weekly wrenching at 6" ($U_6$ + $W_7$). Seedlings receiving no undercutting or wrenching treatment served as a control.

Both treatments produced shorter, thinner-stemmed plant with fewer branches and smaller shoot dry weights. Shoot-root ratios of wrenched seedlings were significantly lower than those of controls but root dry weights were similar for both wrenched and unwrenched seedlings. Undercutting and wrenching also increased cold hardiness.

Average survival of treated seedlings was significantly higher than that of unwrenched controls after one year in the field with the difference being most dramatic on the south slope, where it was increased by 43% ($U_{3+4} + W_{14}$) and 47% ($U_6 + W_7$). The higher survival of wrenched stock is attributed to the improved water economy associated with lower shoot-root ratios and more fibrous root system.

(authors' abstract)

140. Tanaka, Y., J.D. Walstad and J.E. Borrecco. 1976. The effect of wrenching on morphology and field performance of Douglas fir and loblolly pine seedlings. Can. J. For. Res. 6: 453-458.

Second-year Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) and 1st-year loblolly pine (Pinus taeda L.) nursery stock were undercut and wrenched while actively growing in nursery beds. Their morphology and field performance were compared with Douglas fir seedlings that had been undercut only and with loblolly pine seedlings that had been left intact.

The treatment produced shorter, thinner-stemmed loblolly pine seedlings with reduced shoot dry weight. Height, diameter, and shoot dry weight of Douglas fir seedlings were virtually unaffected, but root dry weight was increased substantially. Development of fibrous lateral roots was stimulated in both species. As a consequence, shoot-root ratios were considerably improved, and the seedlings were better conditioned to withstand outplanting. On droughty sites, field survival of Douglas fir was increased by 20 percentage points and loblolly pine by 30 percentage points. Wrenching also extended by several weeks the fall and spring planting periods for loblolly pine and the fall planting period of Douglas fir.

(authors' abstract)

141. Thor, E. 1965. Effects of eight nursery treatments on yellow-poplar seedling characteristics and field performance. U.S. For. Serv. Tree Plant. Notes No. 72. p. 16-18.

The effects root pruning, top pruning and fertilization on the survival and growth of yellow poplar (Liriodendron tulipifera L.) seedlings was investigated. The eight treatments consisted of combinations of two levels of nitrogen application, root pruning at a depth of 6 inches, and top pruning at a height of 5 inches. Top pruning alone or in combination with root pruning did not benefit survival or growth but top pruning in combination with the level of nitrogen in the soil affected root collar diameter. Root pruned seedlings from low nitrogen beds had the poorest survival while high nitrogen levels and root pruning resulted in superior survival.

142. Tinus, R.W. 1981a. Concepts for seedling production and handling being developed in New Zealand. p. 56-60 In Forest Regeneration, Proceedings of the symposium on engineering systems for forest regeneration. ASAE Publication 10-81.

The New Zealand Forest Research Institute has developed a new nursery system which reduces exposure, handling and root damage. The procedures used include square spacing, box pruning (root pruning in three dimensions), and lifting and packing at the nursery bed. The basic principles of the new nursery system should be applicable in North America. Some suggestions for improved mechanization include

an across-the-bed vertical root pruner, a mechanical thinner, and a precision seeder that will produce square spacing.

143. Tinus, R.W. 1981b. Forestation concepts and practices developing in New Zealand. p. 11-16 In Proceedings of Intermountain Nurserymen's Association and Western Forest Nursery Association Meeting, Aug. 12-14, 1980. Boise, Idaho. U.S. For. Serv., Gen. Tech. Rep. Int-109.

This text accompanied a slide presentation showing how New Zealand government and industry are developing a new nursery system backed by substantial research facilities and budget. Beds of radiata pine are precision sown and thinned to square spacing of 7 x 7 cm. This permits "box pruning" which is horizontal undercutting plus vertical root pruning along and across the bed. When lifted, a box-pruned seedling retains virtually all of its roots, and almost every tree is shippable. Since culling and counting are not necessary seedlings can be lifted and packed in the field, eliminating the need for a packing shed. Reduction in exposure and handling of seedlings increases plantation survival and initial growth, and promises to reduce rotation age by 1 year and decrease nursery costs.

(author's abstract)

144. Toliver, J.R., R.C. Sparks and T. Hansbrough. 1980. Effects of top and lateral root pruning on survival and early growth - three bottomland hardwood tree species. U.S. For. Serv. Tree Plant. Notes 31 (3): 13-15.

Water oak (Quercus nigra L.), willow oak (Quercus phellos L.) and pecan (Carya illinoensis (Wangenh.) K. Koch) seedlings were subjected to various lateral root and/or top pruning treatments. Seedlings were top pruned to a height of 15 cm in the nursery or above the last lateral bud in the field. Root pruning was done in the nursery by cutting all lateral roots to approximately 15 cm on either side of the seedlings with a flat spade. At the time of lifting, the tap root of all seedlings was pruned to 15 cm. For any species tested after five seasons outplanted, total height and survival were not significantly affected by lateral root and/or top pruning.

145. Tolley, I.S. 1974. Mechanization of operations in open-ground growing. Int. Plant. Propagators' Soc., Combined Proc. 24: 241-244.

A brief description is given of methods of mechanization of nursery work, mainly for Citrus trees, including seed extraction, sowing, lifting and transplanting, wrenching and lifting for sale (using a winch-operated digger). A self-propelled mechanical 'nursery machine' is also described which carries operators engaged in such operations as trimming and budding at speeds of 6-20 feet/min.

(CAB abstract)

146. Trappe, J.M. 1971. Root pruning conifers in nursery beds: does it increase survival potential? U.S. For. Serv. Tree Plant. Notes 22 (3): 13.

At the end of the second growing season, two varieties of Douglas fir (Pseudotsuga menziesii var. menziesii (Mirb.) Franco) and Pseudotsuga menziesii var. glauca (Beissn.) Franco) seedlings were lifted. The root systems were washed and pruned to a 6-inch maximum length.

Seedlings were potted and placed in a growth chamber programmed to simulate over winter air temperatures at Wind River. When the root systems were examined in March, the seedlings of the var. glauca had initiated clusters of new long roots above the pruning wounds but the residual root system was not bushier. Seedlings of var. menziesii initiated few new roots but small dormant roots began to grow. These observations indicate that no single nursery technique can be guaranteed to produce a given form of root system on all species or even all varieties.

147. van den Driessche, R. 1983. Growth, survival and physiology of Douglas fir seedlings following root wrenching and fertilization. Can. J. For. Res. 13: 270-278.

Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) seedlings were subjected to wrenching treatments during their 2nd year of growth in two experiments at different nurseries on Vancouver Island. Seedlings were wrenched with a fixed blade at 20-25 cm below the bed surface. In experiment 1 wrenching reduced water potential of trees on unirrigated loam soil by an average of 300 kPa during August and September. Wrenched trees lifted in October, which were stored at 2°C until May, showed 25% higher survival than unwrenched trees 1 year after planting. Trees lifted in December had uniformly high survival (98%) and showed no effect of wrenching. Wrenched trees from irrigated plots had lower shoot length relative growth rates (RGR) than unwrenched trees during the year after planting. In experiment 2 wrenching treatments were applied to seedlings, growing in a loamy sand, for different periods between 15 May and 11 September as follows: i/ unwrenched, ii/ early summer, ii/ midsummer, iv/ late summer, v/ all summer. Three different levels of fertilization were applied to each wrenching treatment, and seedlings were lifted for storage at 2°C in October and December. Stored trees and freshly lifted trees were planted at 700 m elevation on 3 March. Wrenching increased root dry weight, particularly when additional fertilizer was applied, but had no measurable effect on cold hardiness or root growth capacity. Nevertheless, late summer wrenching increased survival 5 and 7% above control 1 and 2 years after planting, when average survival was 47% after 1 year. Wrenching had little subsequent effect on new shoot growth of planted trees during 2 years after planting. However, late summer wrenched trees showed significantly more new shoot growth than all summer wrenched trees. Increasing fertilization reduced cold hardiness and survival of cold-stored trees, but increased root growth capacity. Cold hardiness, measured by electrical impedance, was correlated with survival of cold-stored trees after planting ($r^2$=0.82). Root growth capacity, averaged over all fertilizer levels, was closely correlated with survival of stored and freshly lifted trees ($r^2$=0.93). Foliar nutrient concentrations were reduced by wrenching, but fertilization increased nutrient reserves within the seedling.

(author's abstract)

148. Van Dorsser, J.C. 1969. Wrenching, storage and exposure trials at the forest research institute nursery. p. 122-126 In Forest nursery and establishment practice in New Zealand. N.Z. For. Serv., For. Res. Inst. FRI Symp. No. 9.

In a hardening-off trial, autumn-sown Pinus radiata was subjected to various wrenching, topping, and Weedicide-18 regimes in an effort to

produce hardened stock by the middle of March. The seedlings were wrenched weekly, fortnightly, or monthly. Some of the stock was outplanted while the rest underwent treatments involving cold storage, exposure to high temperatures and exposure to sun and wind in efforts to simulate bad nursery and planting site conditions. The results indicated that frequently wrenched (weekly) autumn sown stock should be used if the stock is to stand up to high temperatures, low temperatures, compression or drying conditions.

149. Van Dorsser, J.C. 1973. Equipment for conditioning of planting stock. p. 46-52 In Mechanization of nursery production, forest establishment and tending in New Zealand. N.Z. For. Serv., For. Res. Inst. FRI Symp. No. 13. Vol. 1.

Equipment used for undercutting, wrenching and lateral pruning is described with respect to New Zealand practices. Specifications for the machine as well as modifications and methods are also indicated. Job specifications are described for each operation.

150. Van Dorsser, J.C. 1981. Seedling conditioning. p. 128-142 In Forest nursery and establishment practice in New Zealand. N.Z. For. Serv., For. Res. Inst. FRI Symp. No. 22. Part 1.

Conditioning of bare-rooted trees is aimed at producing stock that is capable of immediate prolific new root growth after planting, so that it survives and makes rapid height growth. The methods employed to produce such stock depend on the growth habit and the growth pattern of the species involved. The timing and intensity of conditioning are influenced by the projected time of lifting. These aspects of conditioning with emphasis on undercutting and wrenching, are outlined for New Zealand tree species and growing conditions.

151. Van Dorsser, J.C. and D.A. Rook. 1972. Conditioning of radiata pine seedlings by undercutting and wrenching: description of methods, equipment and seedling response. N.Z. J. For. 17: 61-73.

Unless Pinus radiata D. Don seedlings are conditioned to withstand transplanting, survival rates can be low. A suitable conditioning treatment consisting of undercutting and wrenching and periodic lateral pruning has been developed at the Forest Research Institute, and this is being applied in most of the larger nurseries in New Zealand. Formerly this was done manually by spade; now a reciprocating undercutter/wrencher drawn by a tractor cuts the seedlings' roots below the surface and a lateral pruner of self-aligning coulters on a tool bar trims vertically between the rows. After being undercut, seedlings are wrenched every 1, 2 or 4 weeks, and lateral pruned every 4 to 6 weeks. Seedlings must be undercut during the growing season, and timed to give a conditioning period of at least 8 to 10 weeks before planting. The effect of such undercutting and wrenching is that shoot growth virtually cases, whereas root growth continues at the same rate, producing a plant with a compact mass of fibrous roots, a high root-shoot ratio, and a hard, woody stem. Carbohydrate levels are also increased.

Although in some nurseries restraints are imposed by soil, climate, and weather, well-conditioned planting stock can be obtained throughout the year by regulating sowing dates and timing of undercutting. Seedlings conditioned in this way were subjected to a range of test conditions in the field and laboratory, e.g. resistance

to root exposure, heat desiccation, cold storage, transplanting into a hot, dry climate. Results indicate that the efficient root system induced by the conditioning regime was the main factor responsible for the higher survival rates; but other factors (e.g. woodiness of shoot, and carbohydrate reserves) are probably also important.
(authors' abstract)

152. Venator, C.R. 1983. Effect of lateral root pruning on development of nursery-grown longleaf pine seedlings. U.S. For. Serv. Tree Plant. Notes 34 (2): 17-19.

The objective of this study was to determine whether systematic lateral pruning would stimulate lateral root development along the taproot of longleaf pine (Pinus palustris Mill.) seedlings. The eleven treatments consisted of combinations of lateral root pruning across and lengthwise to the bed at two, four, six and eight week intervals. All pruning was done by sawing through the soil with a sharpened machete at a middle distance between the seedling rows. The results indicated that lateral root pruning, by itself, will not significantly increase the number of lateral roots within the first 6 inches of the taproot. No root undercutting was done and possible relationships with undercutting and lateral pruning are not known.

153. Venator, C.R. and J.G. Mexal. 1981. The effect of wrenching and planting date on the survival of loblolly seedlings. U.S. For. Serv., Gen. Tech. Rep. SO-34. p. 20-24.

When loblolly pine (Pinus taeda L.) seedlings were approximately 20 cm tall, they were undercut at a depth of 18 cm. The four treatments applied to the seedlings consisted of a control which received only undercutting, and wrenching at a depth of 12 cm at intervals of either twenty-one, thirty-three or forty-five days. All seedlings were lateral root pruned.

Outplanted undercut nonwrenched seedlings survived as well as seedlings wrenched every 21, 33 or 45 days. In a replicated planting, survival was roughly equal for seedlings planted in central Louisiana and southwestern Arkansas for the dates November 15 and January 15. However, survival of the March 15 planting was less in Louisiana. Wrenching did not alter seedling morphology nor did it increase lateral root development. This could have been due to the loss of some fine lateral roots during lifting and that the seedlings may not have been stressed sufficiently by wrenching. The lack of significant differences could also have been the result of the single undercutting which may have been sufficient to shock the seedlings.
(edited authors' abstract)

154. Wahlenberg, W.G. 1925. Forestation Research in Montana and north Idaho. J. For. 23: 589-599.

Recommendations for conducting silvicultural research and valid experiments are reported in this 1925 paper. As well, results of various experiments in such areas as seed extraction, top pruning, seedling production and planting practice in Montana are reviewed. Root pruning trials indicate that pruning should be done at a depth of four to five inches for both yellow pine (Pinus echinata Mill.) and white pine (Pinus strobus L.) stock.

155. Webber, J.E., S.D. Ross, R.P. Pharis and J.N. Owens. 1985. Interaction between gibberellin $A_{4/7}$ and root pruning on the reproductive and vegetative process in Douglas fir. II. Effects on shoot elongation and its relationship to flowering. Can. J. For. Res. 15: 348-353.

Shoot elongation and female flowering response were assessed for gibberellin $A_{4/7}$ ($GA_{4/7}$) and root-pruning (RP) treatments in 9- and 10-year-old Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) seedlings of families with good- and poor-flowering histories. In families with a poor-flowering history, stem injections of $GA_{4/7}$ significantly enhanced elongation of third-whorl terminal shoots but produced no flowering response. In families with a good-flowering history, $GA_{4/7}$ treatment had no effect on shoot elongation but did result in a significant increase in seed-cone buds. In contrast, root-pruning significantly retarded shoot growth in families with both good- and poor-flowering histories and was also the single most effective treatment for enhancing flowering. Combined $GA_{4/7}$ plus RP had a synergistic effect on flowering and $GA_{4/7}$ partially overcame the inhibition of shoot growth caused by RP alone. These results are consistent with a hypothesis that exogenous and endogenous gibberellins are used preferentially for vegetative growth processes, with increased flowering occurring only after a threshold concentration of effect or gibberellins is reached.

(authors' abstract)

156. Wells, T. 1952. Nursery practice at the Green Timbers Forest Nursery Dept. of Lands and Forests, B.C. For. Serv. 7 p.

Nursery practices at Green Timbers Forest Nursery, including seed, seedbeds, watering, weeding, root pruning, shipping of stock and production costs are reviewed. Root pruning is carried out as ear as possible in the spring following the first growing season. The root pruner is a rigid blade placed at an angle of 25° attached to the rear of a tractor. The stock resulting from root pruning cann be distinguished from the more expensive transplants.

157. Wilcox, H. 1955. Regeneration of injured root systems in Noble fir. Bot. Gaz. 116: 221-234.

Roots of one- to three-year-old noble fir (Abies procera Rehd.) seedlings were pruned. Observations were made of the time require for root regeneration, the number of roots regenerated and the general response of the seedling to wounding. Physiological aspec of replacement root development are discussed.

Root pruning of noble fir does not result in a compact fibrous root system. The severance of various roots did not result in lar numbers of laterals along the length of the roots but merely in th origin of replacement roots near the pruned surfaces.

158. Will, G.M., J.C. van Dorsser and D.A. Rook. 1971. Undercutting and r wrenching as a means of producing good Pinus radiata planting stoc in biocide-treated and high fertility soils. Adv. Front. Plant Sc 28: 341-348.

Application of soil sterilants in forest nurseries to control weed or fungal pathogens often results in the production of soft planting stock with low survival potentials. Rather than apply heavy rates of aluminum sulphate as recently advocated, the practice in New Zealand has been to take advantage of the increased growth rates, then by undercutting and root wrenching, direct the food resources of the plant into producing a large fibrous root system. When seedlings are about 10 inches high, a reciprocating root pruner is passed under seedbeds at a depth of 3 inches. Subsequently at regular intervals, a reciprocating wrenching blade is moved through the soil at the same depth as the initial cut. Wrenched seedlings are easily lifted out of the seedbeds, have high survival potentials, and have been proved to be sound, vigorous planting stock. These seedlings have a normal nutrient composition.

(edited authors' abstract)

159. Williams, J. 1975. Water relations of three planting stock types of Pinus caribaea following transplanting. N.Z. J. For. Sci. 5: 87-104.

The response of Pinus caribaea to water stress following transplanting was investigated in a series of experiments in a plant house with three types of planting stock, a/ bare-rooted and wrenched monthly, b/ bare-rooted and wrenched at fortnightly intervals, and c/ potted.

Seedling response, as reflected in relative leaf water content, leaf elongation, and whole plant transpiration was monitored during a drying regime in an environment with a high evaporative demand maintained during daylight hours. Soil water potential and potential evapotranspiration were monitored in conjunction with plant response. Root density and the total length of root per plant were measured at the beginning and end of the drying regime.

The results indicated large differences in the response of bare-rooted and potted planting stock to a regime of drying soil moisture following transplanting. Data for both leaf elongation and transpiration as a function of relative leaf water content indicated that these physiological properties of the three stocks were similar. Modification of the root systems did not greatly alter root density although it did produce large differences in the total length of root per seedling. As differences in the response of planting stock could not be accounted for by differences in root density and the volume of the root zone, it is implied that the seedlings' initial response to water stress was dominated in these studies by the relative water content of the leaf following transplanting.

Interpretation of results in terms of current theory for transfer of water to the root system implies that the effect of root density and the volume of the root zone on the plants' response to water stress requires further study.

(author's abstract)

160. Williams, R.D. 1972. Root fibrosity proves insignificant in survival, growth of black walnut seedlings. U.S. For. Serv. Tree Plant. Notes 23 (2): 22-25.

Test plantings of root pruned black walnut (Juglans nigra L.) seedlings were observed for three and four years for survival, height growth and stem diameter. In the first study, the initial treatments consisted of root radicles being clipped before planting, undercutting when seedlings were 6-8 inches tall, and no pruning.

After 1 year in the seedbeds all seedlings were lifted, root pruned to 10 inches and outplanted. Observations were made for 4 years. In the second trial seedlings were grown in two different soil types with the result that one set of seedlings had a fibrous root system and the other did not. All seedlings were root pruned to 10 inches, outplanted and observed for 3 years.

In the first study, radicle pruned and seedbed pruned seedlings developed multiple taproots while the unpruned seedlings had a normal taproot. After four years, there were no significant differences among the pruning treatments in survival, height or stem diameter. In the second study, the fibrous rooted seedlings did not survive any better or grow any faster than the nonfibrous rooted seedlings. After the 3 year period, the larger diameter seedlings were significantly taller than the smaller diameter seedlings.

161. Wycoff, H.B. 1959. Lateral root pruner. U.S. For. Serv. Tree Plant. Notes 38: 23.

At Mason State Tree Nursery modifications were made to the root pruner that was generally used so that lateral pruning could be done more effectively. Rolling coulters were mounted on a cultivator frame which was in turn mounted on the back of a tractor by means of a 3-point hydraulic lift. The staggered arrangement of the coulters mean that there is less soil compression and lifting action. The lateral root pruner is used after the beds have been undercut.

162. Yamaji, K. and K. Tomioka. 1980. Efect of 9-benzyl adenine on the promotion of rooting in Kuromatsu, Japanese black pine. J. Jpn. For. Soc. 62: 425-428.

Roots of eight-year-old Kuromatsu, Japanese black pine (Pinus thunbergii Parl.) growing at the nursery of the Akanuma Experimental Forest, near Tokyo, Japan, were exposed by digging away the soil. All of the exposed roots were cut off, and each cut surface was treated either with 5 gr of vaseline without the chemical compound (Plot B), or given no treatment with vaseline or vaseline and the chemical compound (Plot C), on April 24, 1975. These trees then were replanted in the same soil in pots. After 218 days, they were exposed again, and the number of newly emerged roots from the cut surfaces or the cut roots were counted and measured. A marked promotion of rooting by a 9-benzyl adenine was observed.
(authors' abstract)

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